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Bachelor's Degree in Aerospace Engineering
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Bachelor's Thesis

"Flight Dynamics of a High-Altitude Balloon"

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Abstract

The present report will be focused on the study of the flight dynamics of a high-altitude balloon, from the effect of elasticity to the prediction of its ascent trajectory. The results are implemented on an application easy to use by a user who wants to know the trajectory, velocity and other parameters, only by indicating the launch site and date.

The report starts explaining the environment in which the project is performed to understand the solution design, along with the methodology that has been followed.

Moreover, a feasibility study is performed analyzing the current framework and situation in regulatory, technical and monetary terms.

The last part includes conclusions and further considerations that the project may have and an innovative proposal arising out from this project: provide coverage to hospitals in developing countries by high-altitude balloons.

Keywords: High-altitude balloon, predictor, wind, atmosphere

LATEX was used as text editor.
Matlab 2018a was used as programming tool.
All images without references are searched in Google by the filter “Free to use, share or modify” or images created with PowerPoint 2016.

Acknowledgments

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From the academic viewpoint, I thank Javier and Carolina, who are the responsible of this project, for their dedication and constant assistance during the whole development. Also, thanks to Alba, Cris and Yoli, my project mates, for the hard-working, for all the headache, and for the great energy that you transmit. This project has joint us even more. I have to mention my class and roommate, Marta, who I met at the begging of this stage and has been my inseparable companion along this trip.

From a more personal perspective, my first mention starts from my school friends, Nuria, Ángela, Marta and Cristina, that besides being far from them, every time we get together it seems that the time have not passed by. Also, I appreciate the support that I have received from Pablo during this last year. By all means, I also have to thank my parents for the effort that they have made, for the understanding of my decisions and for bringing my little brother Alberto to the world, who has been a source of energy and creativity.

I would like to convey my last dedication to my grandparents, Petra, Mercedes and Chencho, for a lifetime dedicated to improving the lives of their children and grandchildren.

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Nomenclature

a	acceleration [$\frac{m}{s^2}$]
C_D	Drag coefficient [-]
F	Force [N]
g	Gravity [$\frac{m}{s^2}$]
h	Height [m]
m	Mass [kg]
P	Pressure [Pa]
r	Position [m]
R	Radius [m]
R_g	Ideal gas constant [$\frac{J}{K \cdot mol}$]
S	Surface area [m^2]
t_0	Initial thickness [m]
T	Temperature [K]
v	Velocity [$\frac{m}{s}$]
V	Volume [m^3]
z	Altitude [m]
λ	Latitude [rad] or [°]
φ	Longitude [rad] or [°]
λ_s	stretch [-]
ρ	Density [$\frac{kg}{m^3}$]

1 Introduction

1.1 Background

1.1.1 Early Balloon Flight

Lighter than air devices have flown from ancient times. Hot-air balloons were known in China from the 3rd century BC, according to Joseph Needham (historian and sinologist), although Kongming lantern is commonly attributed to the strategist Zhuge Liang (180-234 AD). This lamp was used to scare the enemy troops, which were frightened by the thinking that some divine force was helping Liang. [1]

Figure 1: Kongming lantern

This lantern is composed by an oil lamp that is installed under a large paper bag. This bag raises according to Archimedes principle. The theory states that any body submerged in a fluid is acted upon by a force in upwards direction, buoyancy, whose magnitude is equal to the weight of the fluid displaced by the body. [2]

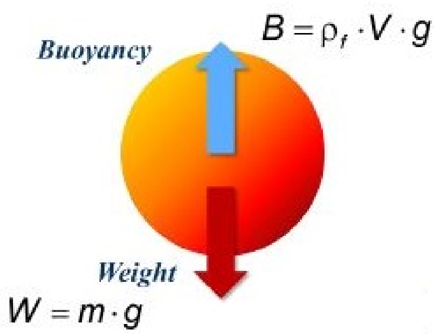

Figure 2: Archimedes' principle [1]

In 1670 Francesco Lana de Terzi (1631-1687) published a book titled Prodromo, which included the first known concept of a flying boat developing the idea of lighter than air flights. His design had a central mast to which a sail was attached, and four masts which had thin copper foil spheres attached to them. The air would be pumped out of the spheres, leaving a vacuum inside, and so being lighter than the surrounding air, would provide lift. Terzi calculated the weight of the spheres and concluded that his device could carry 6 passengers. [3]

It must be mentioned that at the time, no substance lighter than air was known, increasing the creativity of his invention. Moreover, Francesco was aware about the use of these vehicles as a weapon of war and attack cities from the air. He wrote: "*God will never allow that such a machine be built... because everybody realizes that no city would be safe from raids... iron weights, fireballs and bombs could be hurdle from a great height*".

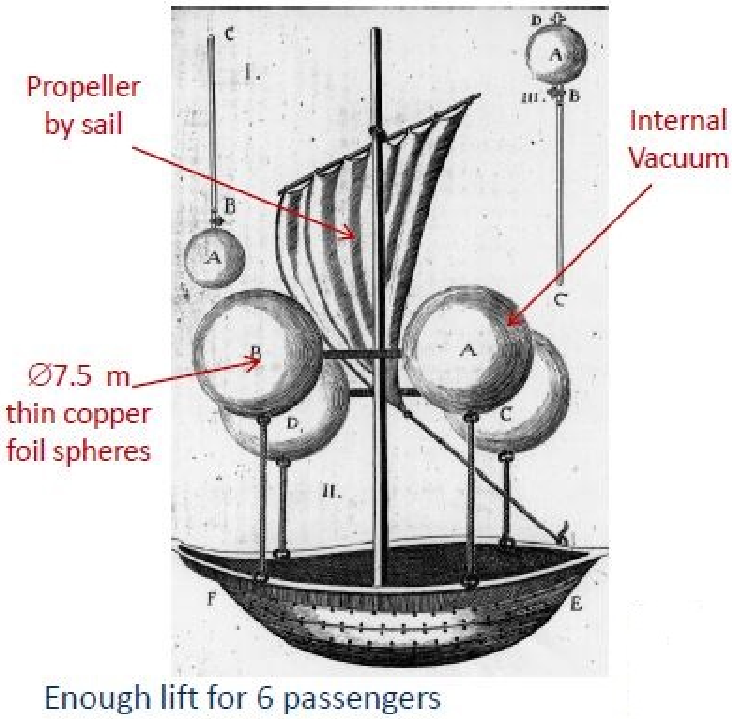

Figure 3: Francesco's concept of flying boat [1]

Hot-air balloon

First hot-air balloon flight was on 5th August 1709. The balloon was designed by Bartolomeu Lourenço de Gusmão (1685-1724), but no exact description already exists.[1]

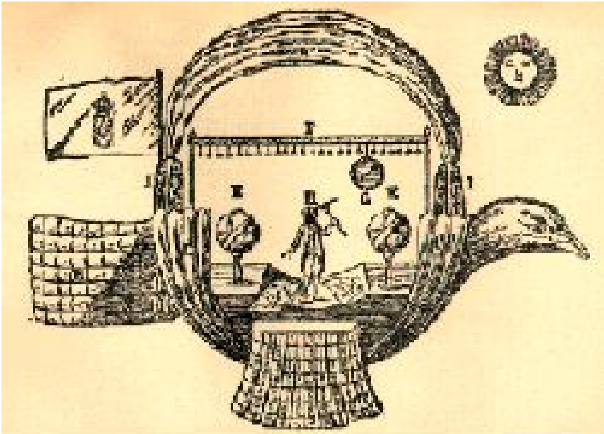

Figure 4: Passarola [1]

Meanwhile, the most famous flight was held on the balloon attributed to the brothers Joshep-Michel (1740-16810) and Jacques-Étienne (1745-1799) Montgolfier. The first passenger flight in a hot-air balloon carrying a sheep, a rooster and a duck occurred on September 19 1783. This flight lasted eight minutes. But, the first free flight by humans ascended on November 21 1783 at Paris, being Jean- Jean-Françoiis Pilatre de Roziere the fist human on air.

Figure 5: Montgolfier hot-air balloon

Hydrogen balloon

Subsequent to hot-air balloons, hydrogen balloons began to grow in importance. In 1671, Robert Boyle rediscovered the reaction of mixing metals with strong acids, previously noted by the alchemist Pasacelsus in the early 1500s. In 1766 Henry Cavendish recognized the hydrogen as a discrete gas. The gas was called *hydro-gen* that means water-former, by Antoine Lavoisier. [4]

The low density of hydrogen seemed to be a great option for filling balloons, so that the first inflation of hydrogen balloon, the Charlière, was on August 27 1783. The balloon raised to 900 m and landed 25 km away. Moreover, on December 1 1783, a hydrogen balloon, carrying Jacques Charles and M.N. Robert, travelled 43 km until it landed safely. [1]

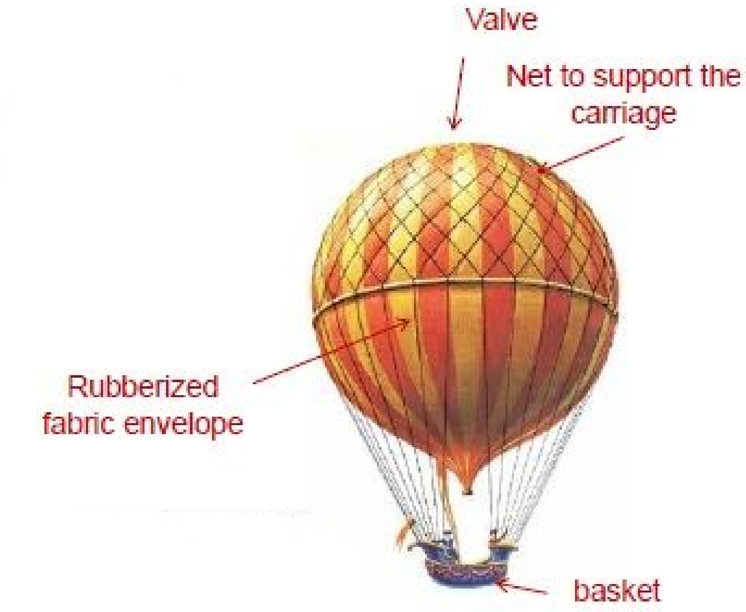

Figure 6: Charles' balloon [1]

Although hydrogen appeared to be the best choice, it reacts quickly with oxygen (to form water) and its future in filling such devices ended when Hindenburg airship burned down in 1937. [5]
Furthermore, Sébastien Lenormand was ahead and tended to demonstrate that hot-air balloons are more reliable than the hydrogen ones. Lenormand crossed safely the English Channel in 1785. [6]

1.1.2 Modern hot air balloon

Nowadays, transport balloons are based on hot-air. The vertical control can be achieved by the pilot, pushing a valve that regulates the flow of gas, and therefore the vertical speed. Moreover, some hot-air balloons have a second propane valve that allows the pilot to burn liquid propane, instead of propane gas, that it is less efficient but also less harmful to the environment. Horizontal control is obtained by vertical movements finding the proper level in which the wind coincides with the desired one. Note that wind currents have different directions at different altitudes.[7]

Figure 7: Modern hot air balloon

1.1.3 High-altitude balloons

High-altitude balloons are unmanned or manned balloons which are filled in most of the cases with helium. They can be also filled with hydrogen or more rarely with methane. The main feature of this type of balloons is that they can reach the Stratosphere. This is why they can be used for meteorological purposes, known as weather balloons, that are launched everyday around the world.

Léon Teisserenc de Bort was pioneer in atmospheric science. He developed one of the first applications of weather balloons. His work consisted of discover the behavior of the tropopause and stratosphere. Moreover, in the 1900s Alfred Wegener, who would later discover Continental drift theory, used kites and balloons to study the upper atmosphere.[8] For him part, James Van Allen, who discovered Earth's Van Allen Belts, also performed many important weather balloon experiments in the 1950's.[9]

Figure 8: Wegener expedition, 1930

In the HAB world, there exists several types of balloons that can be launched with an equipment to record data, such as GPS, camera or sensors. Some experiments have science research objectives, while others take advantage of the flight to test devices in stratospheric environments. High-altitude balloons can be separated as follows:

Open or zero pressure altitude balloons
These balloons present some ducts at the bottom to prevent pressurization. The gas can escape from the balloon to drop the inside pressure inside when it is expanding. These balloons have a maximum flight duration of 7 days because they are limited by the fact that the gas loss occurs mostly at day-night cycling.[10]

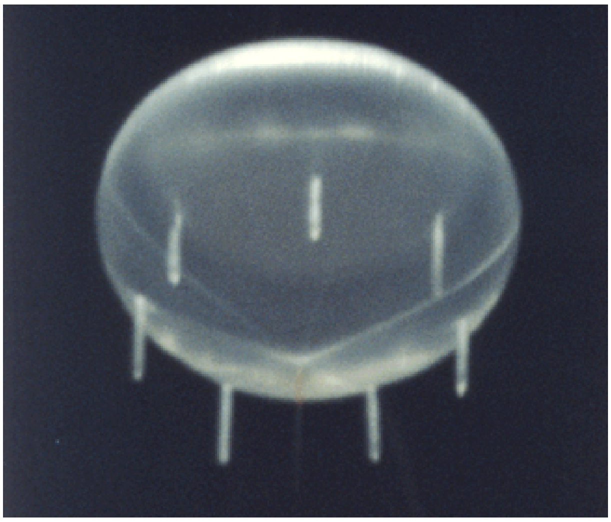

Figure 9: Zero-pressure balloon - NASA [11]

Closed high-altitude balloons

- Pressure balloons:
  They have a different pressure inside and outside the balloon, thereby making that as the pressure outside decreases, the balloon starts to expand until the material do not support this enlargement. This is the type of balloon that is considered for this project.

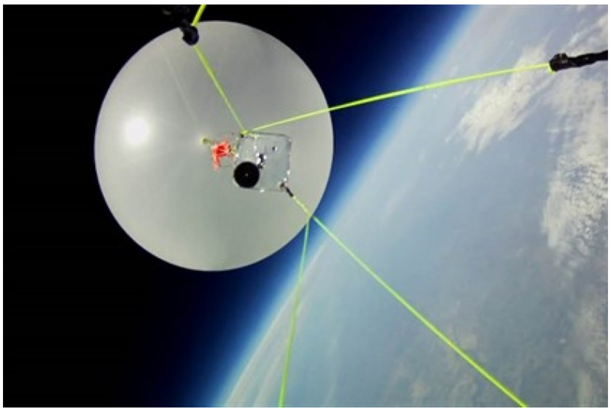

Figure 10: Pressure balloon

- Super-pressure balloons:
  On the other hand, super-pressure balloons are completely sealed. During the ascent the gas pressure builds up and the balloon is expanded until it reaches the highest altitude where the equilibrium is achieved preventing the balloon from continuing the raise. Super-pressure balloons can fly for months. [10]

Figure 11: Super-pressure balloon - CNES [12]

1.2 Motivation

Deep into aerospace science, the motivation of this project came from the fascinating idea of launching a balloon to the Stratosphere. To put into context, the atmospheric layers of the Earth are shown, where the balloon would flight over 30 km height.

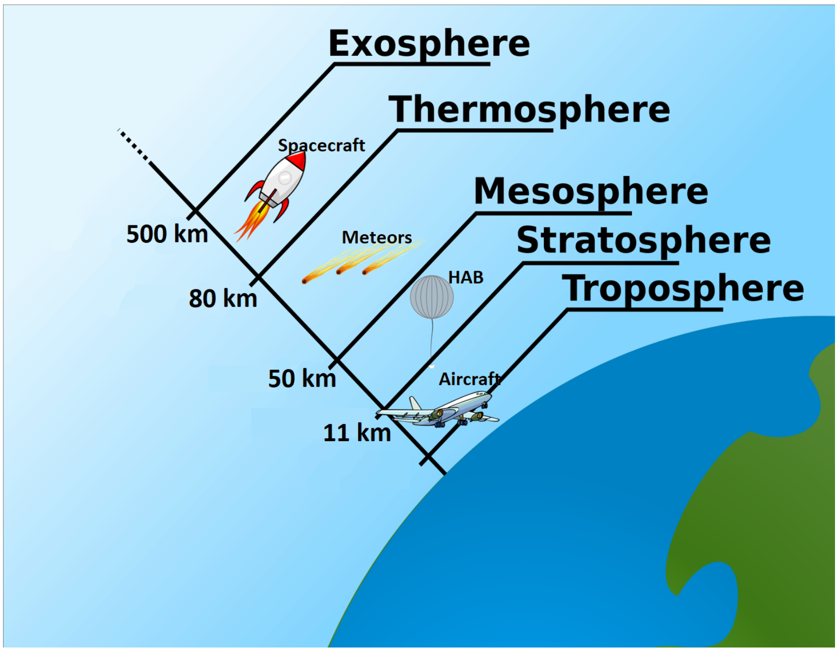

Figure 12: Atmospheric layers

At the beginning, the experiment was divided into different branches, being the branch of aerodynamics whereby this project is focused. When navigating various predictor webpages and studying profoundly how they compute the trajectory of the balloon, lack of precision was found. These predictors assume that the balloon presents a constant ascent rate during the whole flight, leading this project to the creation of a model that will be able to predict trajectories more accurately.

Once the software is developed, the creation of an application is envisaged to provide the information in a more interactive way. Not only will the application show the trajectory of the balloon, but also it would be possible to observe its velocity in different directions, which is not an option in other predictors.

1.3 Scope

First of all, it has to be mentioned that this particular project is set inside a larger experiment. This experiment consists of launching a high-altitude balloon for diverse analyses. It involves different university departments along with students from distinct areas.

The contribution of this project to the entire experiment can be classified in the following purposes:

- Selection of the launched balloon
- Obtaining the amount of helium
- Current situation analysis
- Elastic study along the flight
- Trajectory prediction
- Development of an interactive predictor

On the other hand, it must be said that the experiment will not be possible without the manufacture of a tracker GPS, the design of a proper parachute and a the report of a security study. Moreover, some variables can be analyzed, for example the effect of solar radiation on the balloon. These objectives are going to be fulfilled by the rest of the areas that compose this experiment.

1.4 Regulatory framework

This section provides a deep study of the legal framework of the project by analyzing the regulations in the target market.

1.4.1 Airspace restrictions

States shall establish airspace classification according to their needs since not all space volumes are equally important. According to the restrictiveness, the airspace is classified from A to F; where Class A is the most controlled area. Each state has its own sovereignty over its airspace and can determine the areas through which flight is not recommended, restricted or prohibited. These areas when deactivated have the airspace class of the surrounding space. [13]

- Delta Areas - Danger area. An airspace of defined dimensions within which activities dangerous to the flight of aircraft may exist at specific times. [14]
- Romeo Areas - Restricted areas. An airspace of defined dimensions, above the land areas or territorial waters of a State, within which the fight of aircraft is restricted in accordance with certain specified conditions. [14]
- Papa Areas - Prohibited areas. An airspace of defined dimensions, above the land areas or territorial waters of a State, within which the flight of aircraft is prohibited. [14]

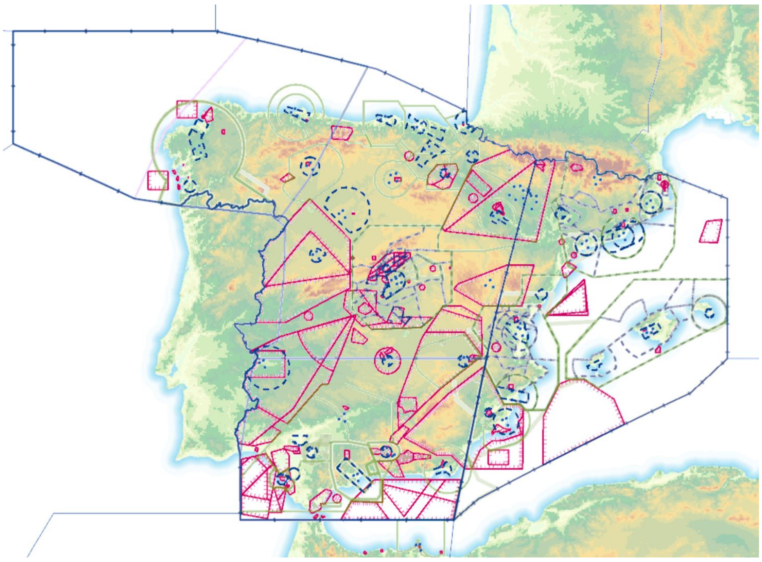

Figure 13: D, R, P Areas in Spain [15]

Some of the areas are permanent and they shall be issued via NOTAM publication. The information of Spain areas are available on the Insignia application by Enaire. Some examples are shown bellow.

AIP
ESPAÑA

ENR 5.1-13
28-MAY-15

ZONAS PELIGROSAS / DANGER AREAS

IDENTIFICACIÓN Y NOMBRE - Límites laterales IDENTIFICATION AND NAME - Lateral limits	Límite superior Upper limit Límite inferior Lower limit	Observaciones / Remarks (Hora de actividad, tipo de actividad, naturaleza del peligro) (Time of activity, type of activity, nature of hazard)
LED2 EL TELENO (León) 422049N 0062332W; 422800N 0061100W; 422300N 0060200W; 421759N 0061656W; 422049N 0062332W.	FL 200 SFC	Ejercicios tiro terrestre y tierra-aire. Terrestrial and ground-air firing exercises. MON, TUE & FRI: 0700-1700 WED & THU: 0700-1700 & 1800-2200

Figure 14: Danger areas Information - Spain [15]

AIP
ESPAÑA

ENR 5.1-5
WEF 21-JUL-16

ZONAS RESTRINGIDAS / RESTRICTED AREAS

IDENTIFICACIÓN Y NOMBRE - Límites laterales IDENTIFICATION AND NAME - Lateral limits	Límite superior Upper limit Límite inferior Lower limit	Observaciones / Remarks (Hora de actividad, tipo de restricción, naturaleza del riesgo, riesgo de interceptación) (Time of activity, type of restriction, nature of hazard, risk of interception)
LER43 TORRIJOS (Toledo) 395303N 0040953W; 395016N 0041729W; 395323N 0042726W; 395802N 0042733W; 400352N 0041856W; 395711N 0040613W; 395303N 0040953W.	5000 ft ALT SFC	Entrenamiento aviones militares. Military aircraft training. 0700-1400 EXC HOL. Otras actividades anunciadas por / Other activities will be announced by NOTAM.

Figure 15: Restrictive areas Information - Spain [15]

AIP
ESPAÑA

ENR 5.1-3
28-MAY-15

ZONAS PROHIBIDAS / PROHIBITED AREAS

IDENTIFICACIÓN Y NOMBRE - Límites laterales IDENTIFICATION AND NAME - Lateral limits	Límite superior Upper limit Límite inferior Lower limit	Observaciones / Remarks (Hora de actividad, tipo de restricción, naturaleza del riesgo, riesgo de interceptación) (Time of activity, type of restriction, nature of hazard, risk of interception)
LEP136 ASCÓ (Tarragona) Círculo de 3 NM de radio con centro en / Circle of 3 NM radius centered on: 411210N 0003407E.	4000 ft ALT SFC	Prohibido el sobrevuelo. Overflying is prohibited. Permanente / Permanent.

Figure 16: Prohibited areas Information - Spain [15]

The balloon shall be launched with extreme caution to not interfere with these areas during the whole flight, taking into account lower and upper limits restrictions. This is the reason why an accurate trajectory prediction is so important for the selection of the launch site.

1.4.2 Operating regulations for high-altitude balloons

It must be mentioned that there is not a specific regulation for high-altitude balloons, but there is for unmanned free balloons. Therefore, this entire section will always refer to these last ones according to Commission Implementing Regulation of EASA (European Aviation Safety Agency).[16]
Since the payload carried by the balloon is less than 4 kg it can be assumed to be a *light* balloon and therefore, only the regulation required for this type of balloon is presented on this paper. [17]

2. ***"General operating rules"***

2.1. *"An unmanned free balloon shall not be operated without authorization from the State from which the launch is made."*

2.4. *"An unmanned free balloon shall be operated in accordance with conditions specified by the State of Registry and the State(s) expected to be overflown."*

2.5. *"An unmanned free balloon shall not be operated in such a manner that impact of the balloon, or any part thereof, including its payload, with the surface of the earth, creates a hazard to persons or property."*

5. ***"Flight notification"***

5.1.2. *"Notification of the intended flight shall include such of the following information as may be required by the appropriate air traffic services unit:"*

- **(a)** *"balloon flight identification or project code name;"*
- **(b)** *"balloon classification and description;"*
- **(c)** *"SSR code, aircraft address or NDB frequency as applicable;"*

(d) *"operator's name and telephone number;"*

(e) *"launch site;"*

(f) *"estimated time of launch (or time of commencement and completion of multiple launches);"*

(g) *"number of balloons to be launched and the scheduled interval between launches (if multiple launches);"*

(h) *"expected direction of ascent;"*

(i) *cruising level(s) (pressure-altitude);"*

(j) *"the estimated elapsed time to pass 18 000 m (60 000 ft) pressure-altitude or to reach cruising level if at or below 18 000 m (60 000 ft), together with the estimated location. If the operation consists of continuous launchings, the time to be included shall be the estimated time at which the first and the last in the series will reach the appropriate level (e.g. 122136Z–130330Z);"*

(k) *"the estimated date and time of termination of the flight and the planned location of the impact/recovery area. In the case of balloons carrying out flights of long duration, as a result of which the date and time of termination of the flight and the location of impact cannot be forecast with accuracy, the term 'long duration' shall be used. If there is to be more than one location of impact/recovery, each location shall be listed together with the appropriate estimated time of impact. If there is to be a series of continuous impacts, the time to be included shall be the estimated time of the first and the last in the series (e.g. 070330Z–072300Z)."*

1.4.3 *22.925* Prohibition on airborne operation of cellular telephones

According to the FCC (ChapterI, Subchapter B, Part 22, Subpart H, 22.925) [18]:

"Cellular telephones installed in or carried aboard airplanes, balloons or any other type of aircraft must not be operated while such aircraft are airborne (not touching the ground). When any aircraft leaves the ground, all cellular telephones on board that aircraft must be turned off."

From all above regulations, it can be concluded that for light unmanned balloons, rules are slight restrictive, however a flight notification have to be emitted to proceed the launching.

2 State of art

2.1 Current framework

For the development of the project, it is required specific materials, technology and space. These items define the framework in which the project is developed and previous investigation is needed.
High-altitude balloons can be made of different materials, such as latex or synthetic rubber. Each material has its own properties (Young's modulus, density, etc.), that are indispensable to study the elastic model. Most of balloons are made of a highly elastic latex material. The properties of this material are, in most cases, not available on the manufacture website and therefore this is a limitation for the project. However, after a deep research, the properties can be estimated based on known latex properties and similar balloons.

Nowadays, technology is growing by leaps and bounds and the software tools required by this project are already developed. In this aspect, the processing time that it is needed for running a routine could be a limitation, nevertheless it is expected to be a short time, around 2 minutes.

On the other hand, the balloon should not intercept prohibited areas and consequently the trajectory prediction is highly important. This will allow to find the best place for launching the balloon and not intercepting undesirable airspace.

2.2 Current situation

Currently, weather balloons are launched every day and different predictor already exist.

2.2.1 Habhub

In the high-altitude balloon science, the most commonly used website is habhub, which includes different tools: a tracker of balloons that stores data (altitude, pressure, etc.) of experiments around the world, a predictor of the trajectory and a burst altitude calculator.

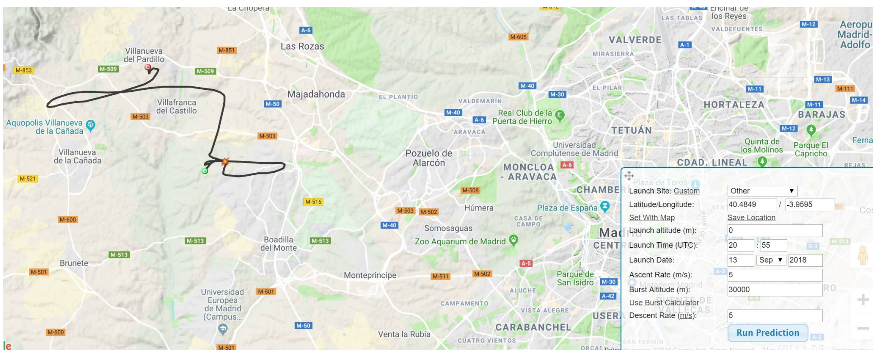

Figure 17: Habhub prediction [19]

The landing predictor is written by CUSF (Cambridge University Spaceflight) and by introducing the date and site of launch, the software predicts the trajectory, the burst site and also estimate its landing. This software takes the wind data from NOAA (National Oceanic Atmospheric Administration) and introduce them into the equations of motion assuming a constant ascent rate. [19]

Another relevant tool is the burst calculator which is able to predict the time to burst and the required filled volume to reach the target burst altitude or ascent rate.

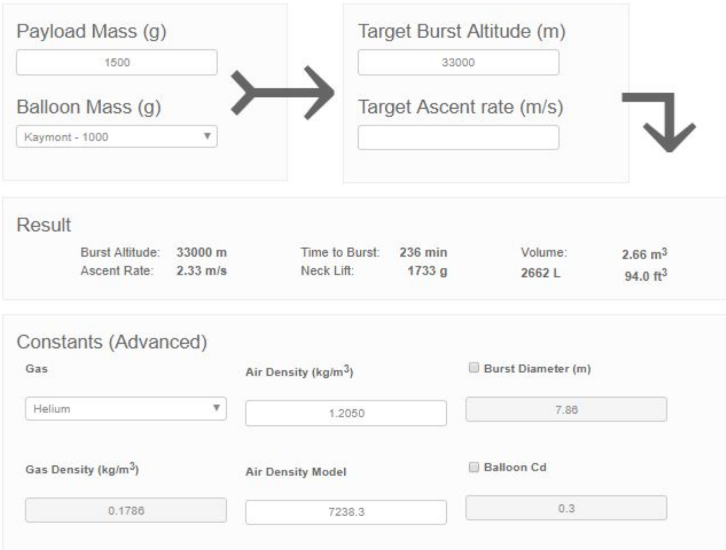

Figure 18: Habhub burst calculator

It must be mentioned that Habhub predictor assumes a constant ascent velocity as it was found from its software code that has been uploaded to *GitHub*.

2.2.2 ASTRA

Another webpage able to predict high-altitude balloon trajectories is called ASTRA (Atmospheric Science Through Robotic Aircraft). This tool has been developed by University of Southampton's and simulates the flight of a latex balloon.

The webpage specifies that the mathematical model is based on ordinary differential equations, where the atmospheric data is obtained from National Oceanic and Atmospheric Administration. Moreover it is said that there are a number of sources of uncertainty, which affect the results of the simulation and therefore a Monte-Carlo procedure is used to provide an indication of the associated error margins. The sources of uncertainty are the followings: [20]

- Drag coefficient of the balloon and parachute.
- Fraction of the balloon that remains attached during the descent.
- Balloon burst diameter.

- Wind perturbations.

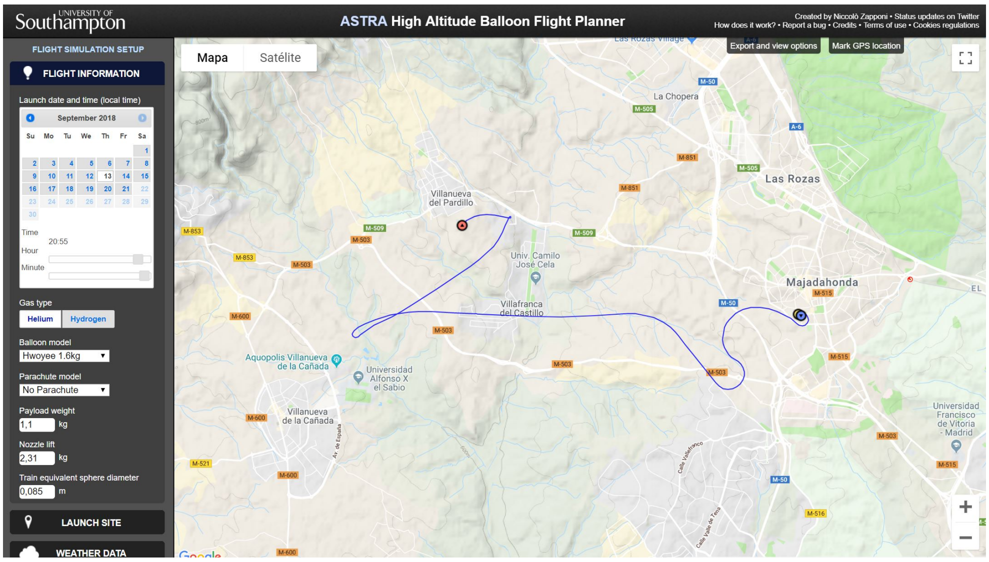

Figure 19: ASTRA prediction

It can be seen that the service allows the user to input many specifications, whether balloon and parachute ones or launch and date as well as the precision of the atmospheric data.

2.3 Solution design

The design of this project is to develop a software that predicts the trajectory of the balloon, taking into account that the ascent rate is not constant anymore. Although this feature will cause a more laborious development, it will improve the accuracy of current predictors.

The solution consists of implementing a MATLAB code that solves the differential equations of motions explained in Methodology section, by ode45 functionality. Moreover, an interactive application was developed, where the user can introduce the launch and date site in the app and the desired plots are displayed on the screen, like the trajectory and velocity evolution of the balloon during the ascent.

3 Methodology

3.1 Balloon selection

As already mentioned, some data are required for the implementation of this project and the first step is to decide the balloon to be launched. The selection depends on the payload that can withstand. It was estimated that the box containing the electronic system was less than 1 kg, therefore a Pawan 1600 balloon was selected for this experiment since it is able to raise 1.1 kg.

After that, the properties of the material to be used are extremely important. High altitude balloons are typically made from latex. Elastomer Polyisoprene (natural rubber latex) is originally from the Amazon region and it is extracted from the sap of "Haeva brasilensis" tree. Then, is spilled in a mold that has the shape of the balloon and later, cured. This material has the enhanced physical properties that natural rubber latex has: exceptional tear, elongation and recovery properties. It is assumed that the selected balloon (Pawan 1600) presents also the properties of this material.

Figure 20: Pawan balloon [21]

With the specifications of the manufacturer and previous data, the initial thickness of the balloon can be calculated with the following formula:

$$t_0 = \frac{m_{balloon}}{4\pi \cdot R^2_{unstretched} \cdot \rho_{balloon}} \tag{1}$$

where,

Balloon mass $[kg]$ - $m_{balloon}$	1.6
Un-inflated radius $[m]$ - $R_{unstretched}$	0.52
Radius at release $[m]$ - $R_{release}$	0.97
Burst radius $[m]$	4.75
Balloon density $[kg/m^3]$ - $\rho_{balloon}$	930
Young's modulus $[MPa]$	0.5
Maximum payload mass $[kg]$ - m_{PL}	1.1

Table 3: Balloon and payload data

Then, the initial thickness is $t_0 = 5.0631$ mm and the volume of the balloon at release can be obtained, 3.8230 m^3, from:

$$V_0 = \frac{4}{3}\pi R^3_{release} \tag{2}$$

3.2 Amount of helium

Another important parameter is the amount of Helium that has to be introduced inside the balloon for its ascent.
Knowing the initial volume, the mass of helium is quite simple to obtain:

$$m_{He} = \rho_{He_{h_{launch}}} \cdot V_0 \tag{3}$$

The density of Helium at the release elevation is obtained from the ideal gas law:

$$PV = nR_gT \tag{4}$$

$$\frac{P}{R_gT} = \frac{n}{V} = \frac{m}{V}\frac{1}{MM} \tag{5}$$

$$\rho_{He_{h_{launch}}} = \frac{MM_{He} \cdot P_{launch}}{R_gT_{launch}} \tag{6}$$

Where,

Helium molecular mass $[kg/mol]$ - MM$_{He}$	$4.003{\cdot}10^{-3}$
Ideal gas constant $[\frac{m^3Pa}{Kmol}]$ - R_g	8.315684
Pressure @650m $[Pa]$- P$_{launch}$	93756.19
Temperature @650m $[K]$- T$_{launch}$	283.835

Table 4: Atmospheric and Helium data

After introducing the density ρ_{He} at the launching elevation (650m), which is 0.15895 kg/m^3, the obatained amount of helium is 0.6077 kg.

However, it must be evaluated whether it is sufficient for the release of the balloon and payload.

The balloon flies because of the buoyancy force. The buoyancy force is the net force that results from the difference between the mass of displaced air and the total mass of the balloon system.

$$L = W_{displaced-fluid} \tag{7}$$

$$\rho_{air}V_{balloon}\cancel{g} = \rho_{He}V_{balloon}\cancel{g} + (m_{balloon} + m_{PL})\cancel{g} \tag{8}$$

$$V_{balloon} = \frac{m_{balloon} + m_{PL}}{\rho_{air} - \rho_{He}} = \frac{1.6 + 1.1}{1.15036 - 0.15895} = 2.7234m^3 \tag{9}$$

$$m_{He_{min}} = \rho_{He}V_{balloon} = 0.4329kg \tag{10}$$

Therefore, the experiment can take place, in terms of helium quantity, since the mass previously calculated is 0.6077 kg, that is greater than the minimum, 0.4329 kg.

3.3 Study of the elastic behavior of the balloon

For any elastic balloon the pressure inside is always a little bit greater than the outside pressure. This is due to the fact that the rubber latex applies a restoring force inwards. The aim of this study is to analyze whether this different in pressure affects the ascent of the balloon.
The pressure inside the balloon is therefore the outside pressure, P_{out}, plus the pressure that it exerted inside the material, ΔP, yielding to the following expression:

$$P_{in} = \Delta P + P_{out} \tag{11}$$

- P_{out} varies with the altitude according to the standard atmospheric model explained bellow.[22]

  1. The standard sea level conditions are:
     ◦ Temperature $T_0 = 15°C = 288.16K$
     ◦ Pressure $P_0 = 101325 N/m^2$
     ◦ Density $\rho_0 = 1.225 kg/m^3$
  2. Acceleration due to gravity is constant, using geopotential altitude
     ◦ $g = g_0 = 9.80665\ m/s^2$
  3. Temperature profile:
     ◦ In the troposphere the temperature decreases linearly with altitude up to -56.5 $°C$ at the tropopause. The gradient slope is called "temperature lapse rate", being equal to D = -6.5$°C/km$ = -6.5·10$^{-3}K/m$
     ◦ In the Stratosphere the temperature remains constant.

     With the previous hypothesis, the following expressions are found for the non-dimensional variables (θ, δ, σ), with altitude (z) in meters:

  4. The air is dry and a perfect gas:

$$pV = nRT, \tag{12}$$

where the universal or ideal gas constant $R_g = 8.3144598\ \frac{J}{Kmol}$

Troposphere (z$\leq$ 11000m)

$$\theta = \frac{T}{T_0} = 1 - \frac{D}{T_0}h = 1 - 2.225569 \cdot 10^{-5} z \tag{13}$$

$$\delta = \frac{P}{P_0} = \theta^{-g/(DR_g)} = \theta^{5.2561} \tag{14}$$

$$\sigma = \frac{\rho}{\rho_0} = \theta^{-g/(DR_g)-1} = \theta^{4.2561} \tag{15}$$

Tropopause (z = 11000m)

$$\theta_{tpp} = 0.75187 \tag{16}$$

$$\delta_{tpp} = 0.22336 \tag{17}$$

$$\sigma_{tpp} = 0.29707 \tag{18}$$

Stratosphere (z≥ 11000m)

$$\theta = \theta_{tpp} = 0.75187 \tag{19}$$

$$\delta = \delta_{tpp} exp\left(\frac{g(z-11000)}{R_g T_{tpp}}\right) = 0.22336 exp\left(-1.57688 \cdot 10^-4(z-11000)\right) \tag{20}$$

$$\sigma = \frac{\delta}{\theta_{tpp}} = 1.33001\delta \tag{21}$$

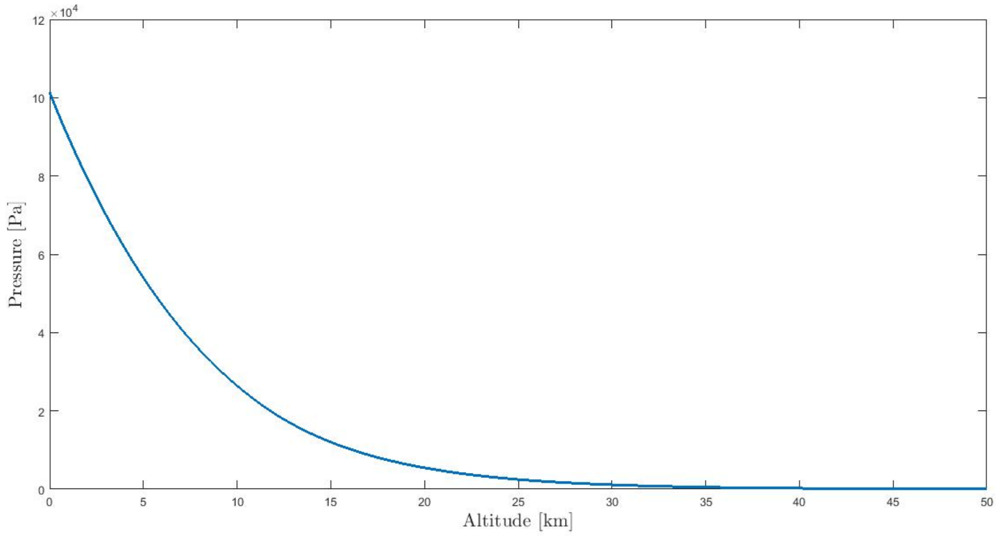

Figure 21: Evolution of the outside pressure with altitude

- P_{in} can be calculated by the ideal gas law, equation 4, knowing the number of moles of helium and the volume and temperature evolution during the ascent as a function of the altitude.
- ΔP is the focal point of this study and it is known as the membrane pressure. It changes depending on the elastic model and it will be analyzed in the following sections.

In order to assess the importance of elasticity, some parameters are going to be studied with and without taking into consideration the elastic effects:

1. Membrane pressure
2. Radius evolution
3. Maximum lift mass
4. Ascent velocity

The amount of mass lifted by the balloon can be expressed as the mass displaced fluid by Archimedes' principle:

$$m_{lift} = \rho_{air} V_{balloon} \tag{22}$$

Where the volume of a sphere is:

$$V_{balloon} = \frac{4}{3}\pi R^3 \tag{23}$$

On the other hand, the vertical drag follows this equation:

$$D_v = \frac{1}{2}\rho v_z^2 C_D S \tag{24}$$

Where C_D is the drag coefficient of a sphere, 0.47 and S is the surface of a sphere. Then, the velocity in the vertical direction can be computed:

$$v_z = \sqrt{\frac{2D_v}{\rho C_D S}} = \sqrt{\frac{2mg}{\rho C_D \pi R^2}} \tag{25}$$

By this physical explanation, it can be seen that the lift mass and the ascent velocity are dependant on the radius evolution, that in turn depends on the membrane pressure. Therefore, a deep analysis of ΔP and consequently of the radius will be performed.

3.3.1 Non-elastic model

A non-elastic material implies that the inside and outside pressures are equal, being the membrane pressure negligible, $\Delta P = 0$.

$$P_{in} = P_{out} = P \tag{26}$$

The evolution of the radius can be evaluated as follows:

$$PV = nR_g T \tag{27}$$

$$nR_g = const = \frac{PV}{T} = \frac{P_0 V_0}{T_0} \tag{28}$$

$$\frac{P \cancel{\frac{4}{3}\pi} R^3}{T} = \frac{P_0 \cancel{\frac{4}{3}\pi} R_0^3}{T_0} \tag{29}$$

$$R = R_0 \left(\frac{T}{T_0} \frac{P_0}{P} \right)^{1/3} \tag{30}$$

From equation 28:

$$\frac{P_0}{T_0} = \frac{nR_g}{V_0} = \frac{3nR_g}{4\pi R_0^3} \tag{31}$$

Introducing this term into equation 30:

$$R = \left(\frac{3nR_g}{4\pi} \cdot \frac{T}{P} \right)^{1/3} \tag{32}$$

3.3.2 Hyperelastic models

Hyperelastic material is defined as the one whose relation between stress and strain is derived from a strain energy density function, W. Moreover for the study of the hyperelastic models, some assuptions are made:[23]

- The balloon is considered to be as a spherical thin shell
- Incompressible material: hydrostatic stress does not become too large and so the admissible deformations must be isochoric (constant volume)
- Isotropic material: physical properties do not depend on the analyzed direction
- Non-linear elastic material

Assuming the balloon remains spherical during the ascent, the membrane pressure for a material with the previous assumptions is defined as a function of the stretch $\lambda_s = R/R_0$ by the following expression.

$$\Delta P(\lambda_s) = \frac{4t_0}{R_0} \left(\lambda_s^{-1} - \lambda_s^{-7} \right) \left(\frac{\partial W}{\partial I_1} + \lambda_s^2 \frac{\partial W}{\partial I_2} \right) = \frac{t_0}{R_0 \lambda_s^2} \frac{\partial W}{\partial \lambda_s} \tag{33}$$

Where r_0 and t_0 are the uninflated radius and thickness respectively. Also the strain invariants are defined as:

$$I_1 = 2\lambda_s^2 + \lambda_s^{-4} \tag{34}$$

$$I_2 = \lambda_s^4 + 2\lambda_s^{-2} \tag{35}$$

Then, the equation 11 for a hyperelastic model reads as follows:

$$P_{in} = \Delta P(\lambda_s) + P_{out} \tag{36}$$

Mooney-Rivlin model

As already mention in equation 33, the membrane pressure will depend on the strain-energy density function W, that it is defined differently according to the model. [23]
The classical W is the Mooney-Rivlin strain-energy for incompressible rubber:

$$W = \frac{1}{2}\mu \left[\alpha(I_1 - 3) + (1 - \alpha)(I_2 - 3) \right] \tag{37}$$

Rearegement equation 36 the outside pressure

$$P_{out}(z) - \frac{nRT(z)}{\frac{4}{3}\pi R^3} + 2\mu\frac{t_0}{R_0}\left(\lambda_s^{-1} - \lambda_s^{-7}\right)\left(1 + \frac{1-\alpha}{\alpha}\lambda_s^{-2}\right) = 0 \tag{38}$$

Where μ is the shear modulus and α a dimensionless parameter (μ=300 kPa and α=10/11).
r_0 is the unstretched radius that is given by the manufacturer. The initial thickness, t_0 can be estimated by:

$$t_0 = \frac{m_{balloon}}{4\pi R_0^3\rho_{balloon}} \tag{39}$$

Equation 38 contains two variables that depends on the altitude and two unknowns (P_{out} and λ) that can be solved by an iterative process.

This model has been experimentally checked that it is useful for rubber materials at small stretches λ, but it is not adequate for large strain subjection.

Gent model

On the other hand, Gent is able to model the stiffening that the rubber undergoes as it approaches its breaking point. However, the parameters are more laborious to measure precisely without destructing the balloon. [23]

The Gent strain-energy density is defined as:

$$W = \frac{\mu}{2}\left[-\alpha J_m ln\left(1 - \frac{I_1 - 3}{J_m}\right) + (1-\alpha)(I_2 - 3)\right] \tag{40}$$

J_m is the limiting chain extensibility parameter that corresponds to the maximum stretch reached by the material.

$$J_m = 2\lambda_{s_m}^2 - \lambda_{s_m}^{-4} - 3 \tag{41}$$

For the case of $\alpha = 1$, first Gent proposal, it is obtained the two-parameter generalized neo-Hookean model, that after a rearrangement, equation 36 becomes:

$$P_{out}(z) - \frac{nRT(h)}{\frac{4}{3}\pi R^3} + 2\eta\frac{t_0}{R_0}\left(\lambda_s^{-1} - \lambda_s^{-7}\right)\frac{J_m}{J_m - (2\lambda_s^2 - \lambda_s^{-4} - 3)} = 0 \tag{42}$$

The same procedure as Mooney-Rivlin equation is followed to solve Gent model.

3.4 Dynamics of the balloon

The balloon is considered to be a point particle along the whole trajectory with a mass m moving in the three-dimensional space under a known force $\vec{F}$. The balloon has three degrees of freedom, which means that three independent parameters are required to fully determine its position, P.

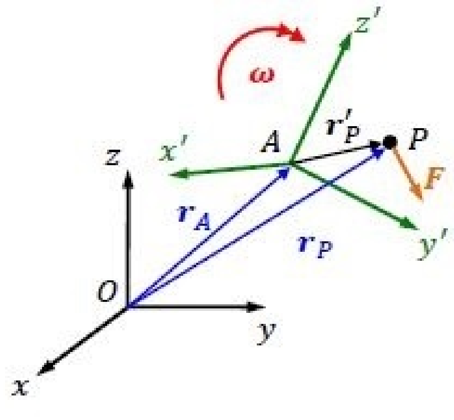

Figure 22: Relative motion

It must be mentioned that the Earth inertial reference frame has its origin at the center of the Earth O. However, the trajectory wants to be computed from a non-inertial reference frame attached to the surface of the Earth, point A. Point A rotates around Earth axis at a constant, in module and direction, angular velocity $\vec{\omega}$ (angular acceleration, $\vec{\alpha} = 0$). This fact generates inertia forces, that the main one is Coriolis force ($2\vec{\omega}$ x $\vec{v}$). Since the day duration is much longer compared with the balloon flight, the induced velocity will be small compared with the velocity of the balloon. Therefore, inertia forces, F_I are assumed to be negligible.

$$m\vec{a_P}' = \vec{F} + \cancel{\vec{F_I}} \tag{43}$$

Then, the equations of motion are simply:

$$m\frac{d^2\vec{r_P}'}{dt^2} = \vec{F} \tag{44}$$

This vector equation can be expressed as three independent scalar equations by projecting in three independent directions. The forces applied to the balloon are the drag D, thrust T and weight W that have to be decomposed along their respective axes. [24]

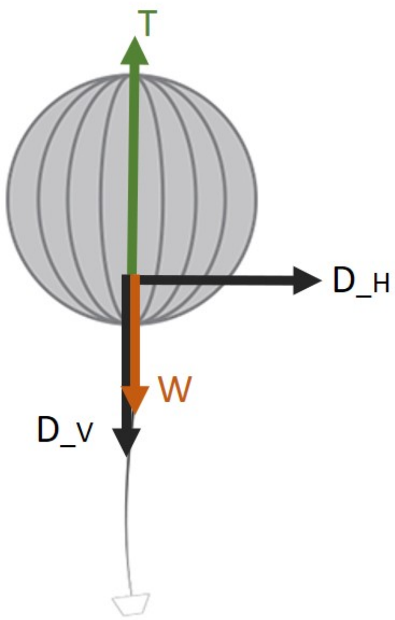

Figure 23: Forces applied to the balloon

3.4.1 Cartesian coordinates

Considering Cartesian coordinates as the independent directions x,y,z, the scalar equations can be expressed as a system of 6 first-order ordinary differential equations:

$$m\frac{d\dot{x}}{dt} = F_x = D_x = \frac{1}{2}\rho(z)\left(v_{w_x}(z) - v_x\right)^2 SC_D \tag{45}$$

$$m\frac{d\dot{y}}{dt} = F_y = D_y = \frac{1}{2}\rho(z)\left(v_{w_y}(z) - v_y\right)^2 SC_D \tag{46}$$

$$m\frac{d\dot{z}}{dt} = F_z = T - W - D_z = V(h)\rho(z)g - mg - \frac{1}{2}\rho(z)v_z^2 S(z)C_D \tag{47}$$

$$\frac{dx}{dt} = \dot{x} = v_x \tag{48}$$

$$\frac{dy}{dt} = \dot{y} = v_y \tag{49}$$

$$\frac{dz}{dt} = \dot{z} = v_z \tag{50}$$

There is no wind in z direction, being therefore the wind velocity decomposed in x and y directions v_{w_x} and v_{w_y} respectively.
The surface area S and volume V of the balloon is defined as a function of its radius R:

$$S = \pi R^2(z) \tag{51}$$

$$V = \frac{4}{3}\pi R^3(z) \tag{52}$$

The position of the balloon is computed by solving the six first-order ordinary differential equations. The solution will depend on six arbitrary constants that are obtained by the initial conditions in position and velocity: $\vec{r}(t=0) = \vec{r_0}$ and $\vec{v}(t=0) = \vec{v_0}$.

3.4.2 Ellipsoidal / Geographic coordinates

On the other hand, ellipsoidal coordinates (latitude, longitude and altitude) are quite useful for representing the balloon trajectory. This is why it is needed to convert Cartesian into Geographic coordinates. The way to do that is to take an initial point on the Earth's surface φ_0, λ_0 and z_0 and then, transformation factors R_u and R_v are defined. They represent the displacement in the latitude and longitude coordinates.

$$R_u = \frac{\sqrt{(X_{\Delta_\lambda} - X_0)^2 + (Y_{\Delta_\lambda} - Y_0)^2 + (Z_{\Delta_\lambda} - Z_0)^2}}{\Delta} \tag{53}$$

$$R_v = \frac{\sqrt{\left(X_{\Delta_\varphi} - X_0\right)^2 + \left(Y_{\Delta_\varphi} - Y_0\right)^2 + \left(Z_{\Delta_\varphi} - Z_0\right)^2}}{\Delta} \tag{54}$$

Where $[X_{\Delta_\varphi}, Y_{\Delta_\varphi}, Z_{\Delta_\varphi}]$ and $[X_{\Delta_\lambda}, Y_{\Delta_\lambda}, Z_{\Delta_\lambda}]$ denotes the position on the surface of the Earth after a small displacement from the initial point.

$$\Delta_\varphi = \varphi_0 + \Delta \tag{55}$$

$$\Delta_\lambda = \lambda_0 + \Delta \tag{56}$$

Being therefore latitude and longitude in radians:

$$\varphi = \tfrac{y}{R_v}, \qquad \lambda = \tfrac{x}{R_u}$$

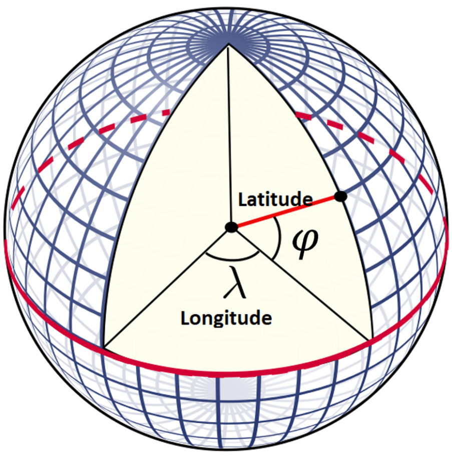

Figure 24: Geographic coordinates

3.4.3 Wind data collection

NOAA (National Oceanic and Atmospheric Administration) is an agency of the United States that researches from the Sun to the ocean, to keep the public aware of the changes around their environment. NOAA provides weather forecasts, ocean and coast data to study the climate change, among others.[25]

Figure 25: NOAA [25]

The wind database is stored in NOMADS (NOAA Operational Model Archive and Distribution System), where global and regional models of statistical and forecast wind data can be found. The Global Forecast System (GFS) has been used for the national weather since 1980 and it is continuously improved by Global Climate and Weather Modeling Branch, that manages a research program of the environment.[26]

The output provided by NOMADS is a " grib" file that contains the global wind velocity data. It is upgraded every 6 hour and provides a forecast with an interval from 3-h to 240-h with a maximum precision of 0.25 degree (in longitude and latitude) with 46 vertical standard pressure levels.[26] The data have to be downloaded and stored in structures and matrices to process them. The way to do that has been performed with the help of " nctoolbox", that provides read-only access to GFS data model dataset in Matlab.

Data interpolation

From the launch site to the burst altitude, the balloon passes throughout different longitudes and latitudes. GFS only provides 0.25 degree precision, which means that an interpolation has to be made to obtain wind data during the whole ascent.

The way to proceed starts by storing the pressure altitudes GFS data from its minimum to the maximum. After that, the launch elevation can be transformed into its pressure-altitude, that must be allocated within this range of pressure-altitudes. Then, a weight coefficient "ch" is computed to know how far from the minimum or maximum pressure-altitude this datum is.

$$ch = \frac{P - h_{pv}(idxdh - 1)}{h_{pv}(idxdh) - h_{pv}(idxdh - 1)} \tag{57}$$

Where idxdh is the minimum value of P that is greater than h_{pv}.

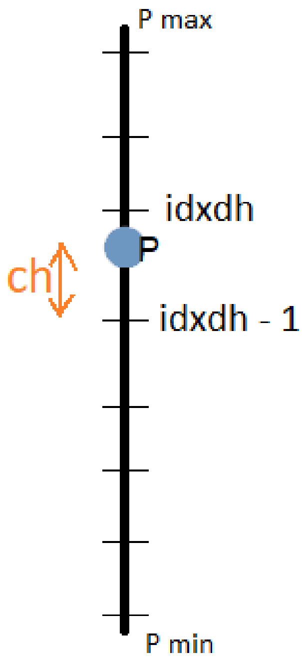

Figure 26: Interpolation line pressure-altitude

Same procedure is developed for latitude and longitude, with their own weight coefficients," clat" and " clong" respectively.
This procedure enables to create a virtual parallelepiped whose vertices are computed in such a way that it encloses the data before and after the desired data; in altitude, longitude and latitude directions. This can be seen easily in the following picture:

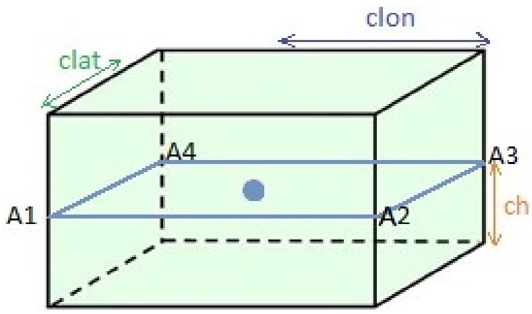

Figure 27: Interpolation parallelepiped [27]

After that, the intermediate plane is selected and by linear interpolation, the desired datum can be obtained.

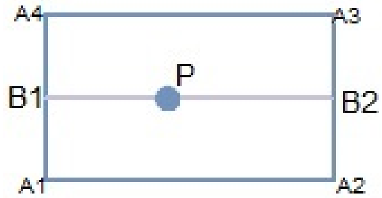

Figure 28: Interpolation rectangle

Since obtaining a proper wind data is highly important, a testing procedure has been followed to verify the method. A specific latitude and longitude is selected showing that the interpolation is correctly performed as the interpolation line fits the real wind data along altitude.

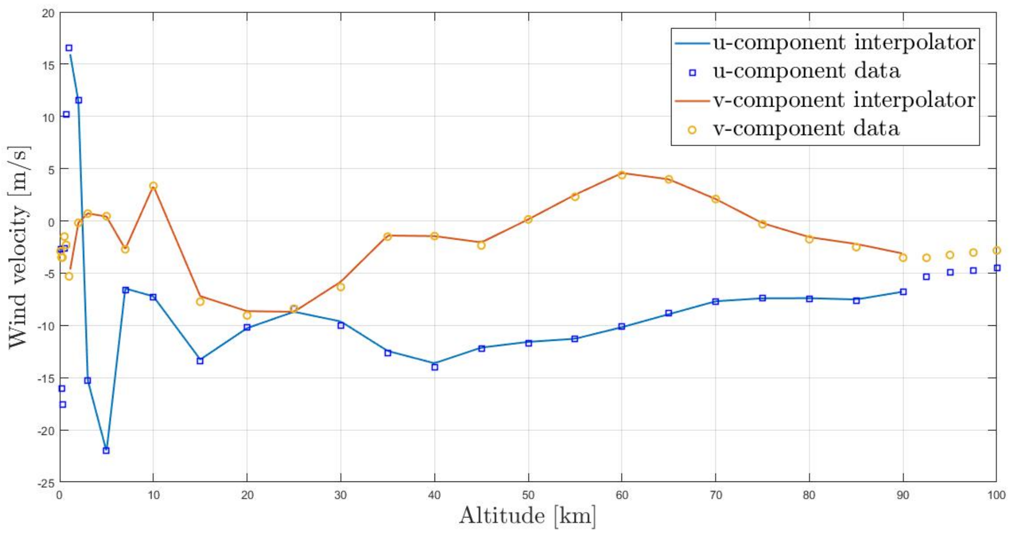

Figure 29: Interpolate result

4 Results

4.1 Study of the elastic behavior of the balloon

As previously explained, an analysis of the importance of elasticity is performed evaluating each of the variables that may affect the trajectory of the balloon. For this study, the launching site was selected at 650 m of elevation and the total mass of the balloon is 2.7 kg with the material previously specified. The project balloon is expected to explode at 30 km and therefore this study will be focused up to this limit.

4.1.1 Membrane pressure

Regarding the membrane pressure, recall that it is the difference between the inlet and outer pressure, it can be appreciated some differences depending on the model.

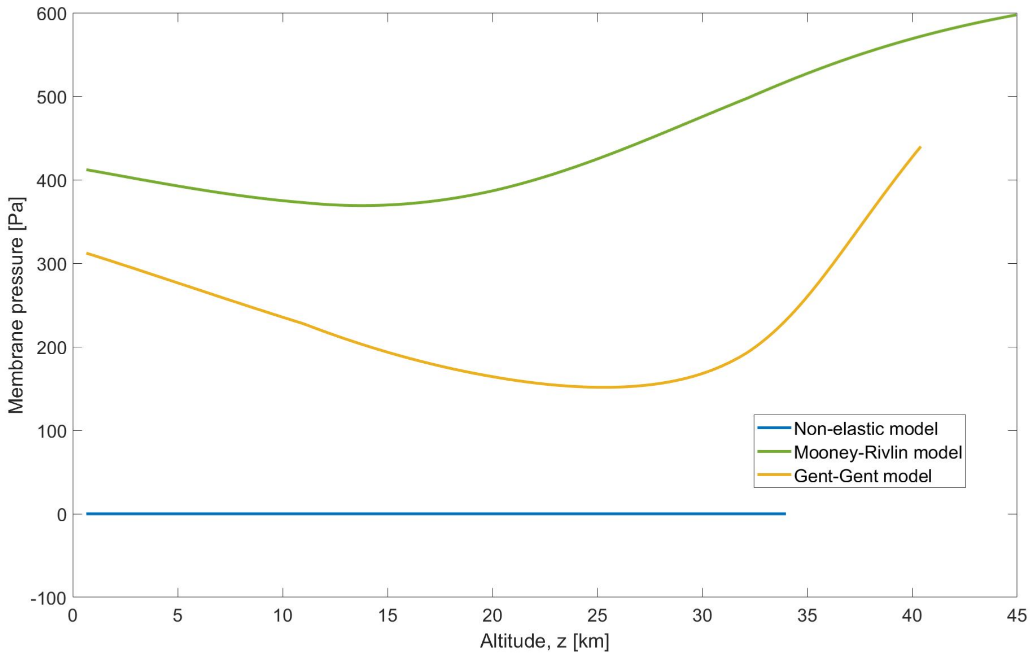

Figure 30: Membrane pressure evolution with altitude

In the above figure, it can be seen that from the beginning of the ascent until the balloon reaches 30 km, Gent model membrane pressure becomes more and more negligible, reaching a minimum of 100 Pa comparing it to the atmospheric pressure at sea level (101325 Pa).
Similar behavior happens to Mooney-Rivlin membrane pressure, which is reduced until 20 km of altitude. Note that at burst altitude (30 km approx.), Mooney-Rivlin membrane pressure is about 500 Pa, which is already a small value compared with atmospheric pressure at sea level.

The effect of membrane pressure seems to appear at higher altitudes, where both elastic models increase rapidly to larger values. Therefore, it can be concluded that membrane pressure does not contribute substantially to the performance of the balloon.

4.1.2 Radius evolution

For the radius analysis, it can be seen in figure 31 that all three models follow the same increasing evolution. This fact is due to pressure tendency balance between the helium inside the balloon and the air outside. Since the outside pressure is continuously decreasing (figure 21), the helium that is inside the balloon tends to expand reducing the internal pressure.
It is coherent that the elastic models exhibit less radius increase at the same height because these models take into account the pressure exerted by the latex, which delays the radius growth. This graph is aligned with figure 30 because as the membrane pressure increases, the radius tends to rise more slowly. Therefore, Mooney-Rivlin model present the largest membrane pressure and the slowest radius evolution.

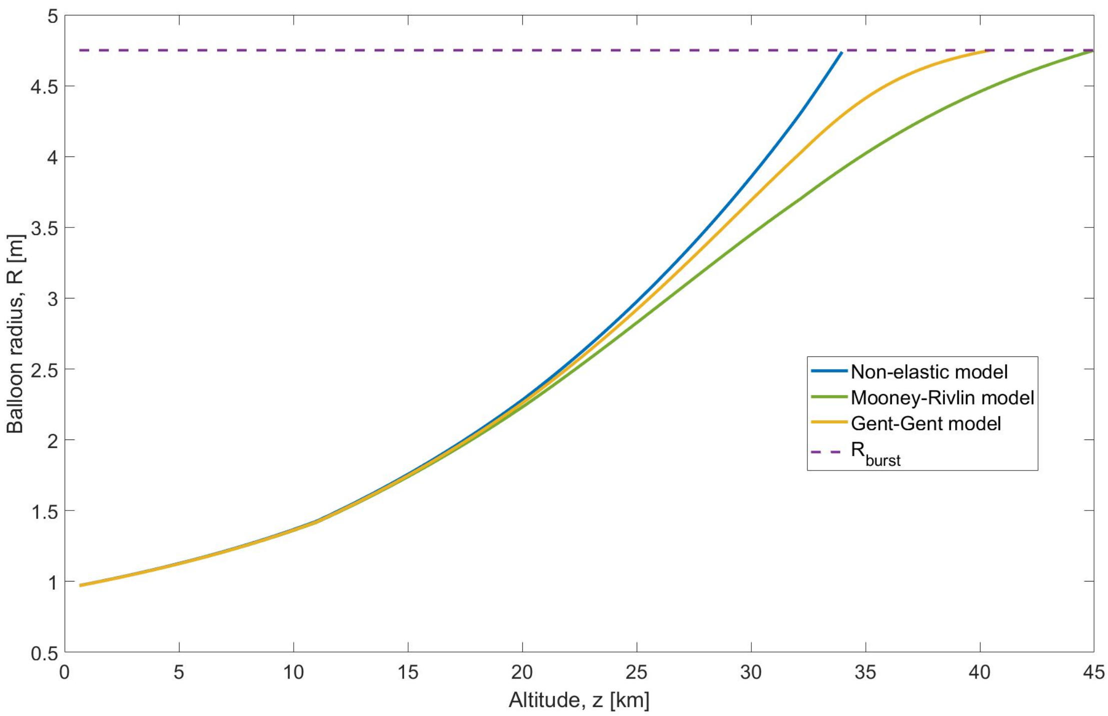

Figure 31: Radius evolution with altitude

4.1.3 Maximum lift mass

The lift mass stands for the mass of volume of air that is displaced by the balloon. For the case of non-elastic model, the lift mass is maintained constant along the ascent. This can be explained by the fact that the volume is inversely proportional to the density and therefore equation 22 is maintained constant.
For their part, the elastic models undergo a decrease on the lifted mass. As previously explained, the radius increase is slower than the case of non-elastic model, producing a less volume expansion than the density decrease along the ascent. For this reason, the lift mass drop in Mooney-Rivlin model (from 4.5 to 0.9 kg) is greater than for Gent model (from 4.5 to 1.25 kg).

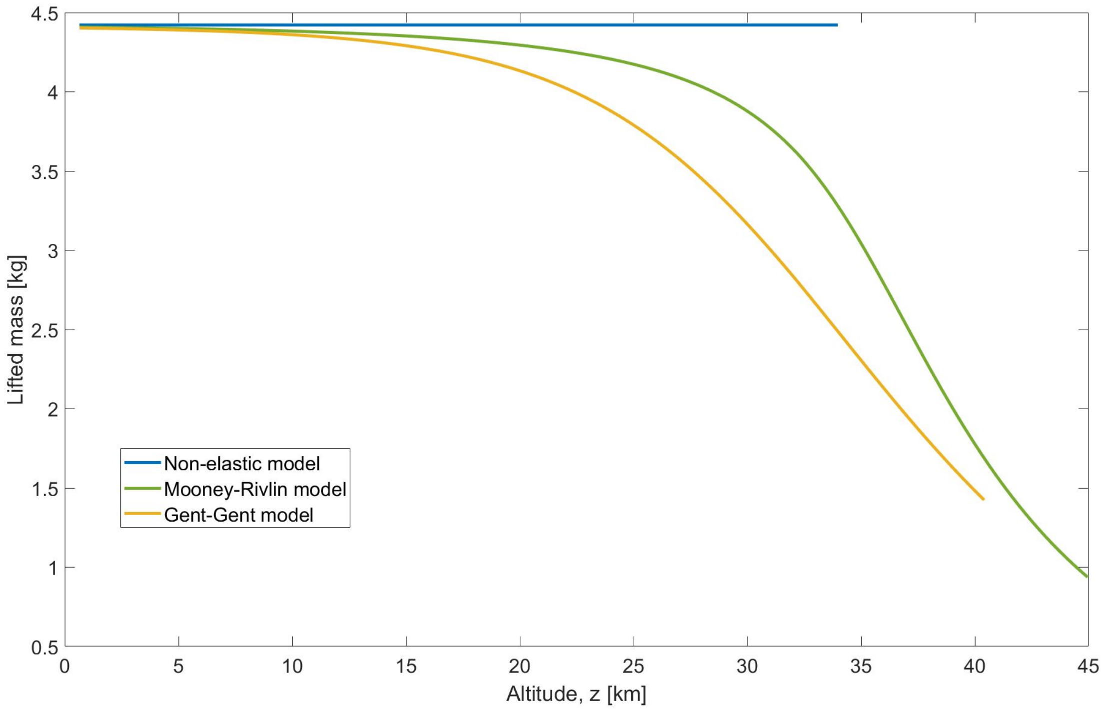

Figure 32: Lifted mass evolution with altitude

4.1.4 Ascent velocity

The next variable to analyze is the ascent rate that increases with height. As the balloon raises, the air density undergoes a drop yielding to a reduction in drag greater than the lift does. This fact produces an increase of the velocity.

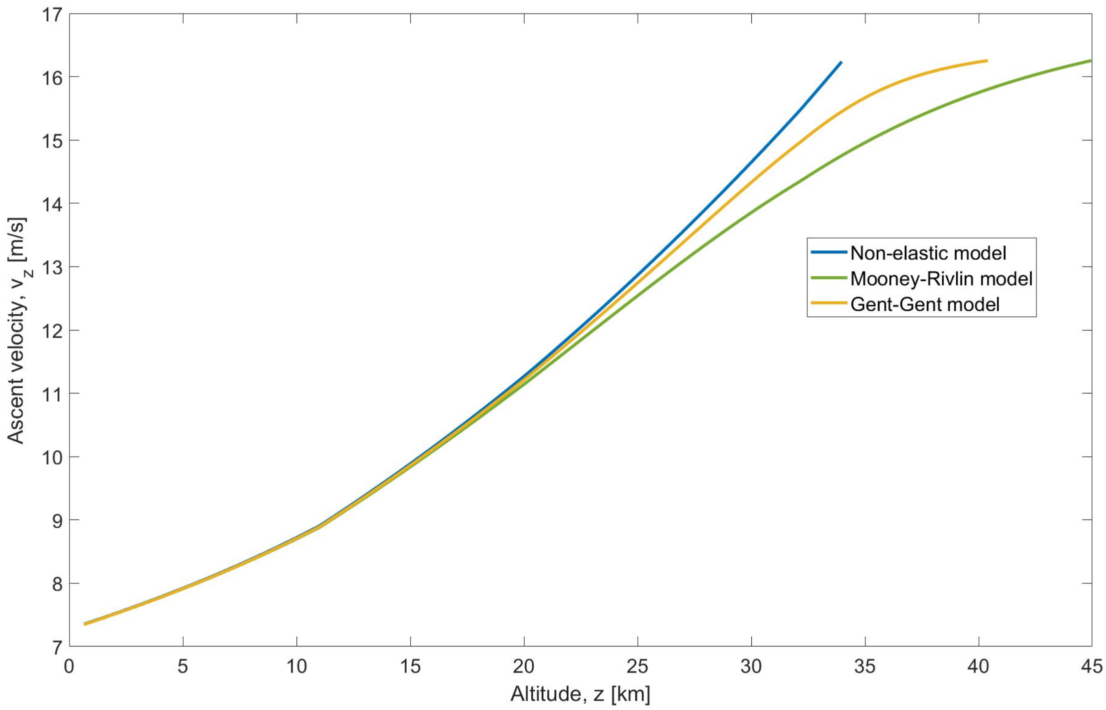

Figure 33: Ascent velocity with altitude

4.2 HAB Ascent Predictor

One of the main objectives of this project is to implement an application that allows the user for predicting the ascent of a high-altitude balloon when introducing the launch site and date. Also the specifications of the balloon (mass, payload mass, etc.) would be read from a text file or similar, that is left as a further development.

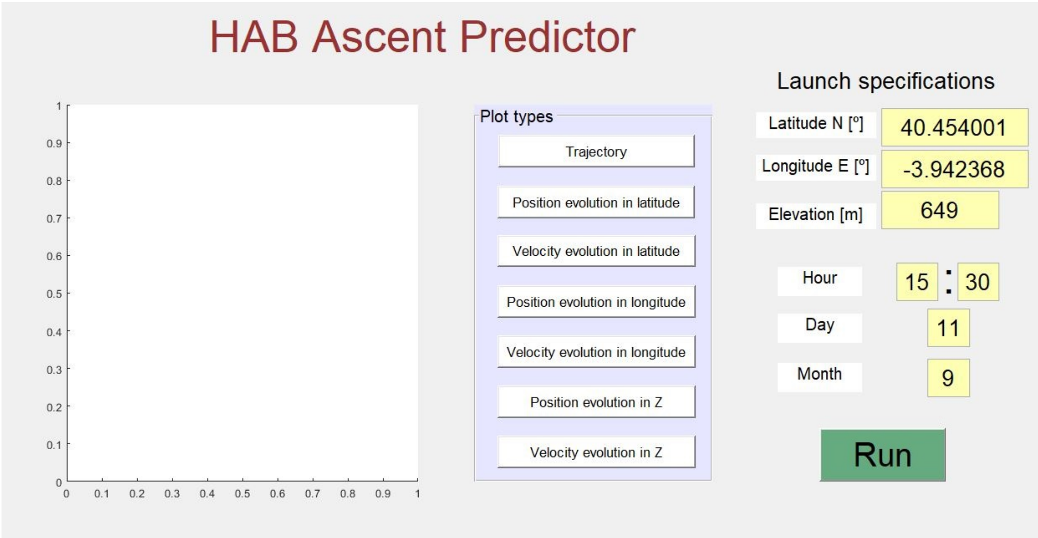

Figure 34: HAB Ascent Predictor Application

After that, the user has to click "Run" to start the prediction. When the software finishes the process, the user clicks on each of the requested plots and the variable evolution along time is shown on the left side of the screen. The user is also allowed to rotate the graphs as user demands.

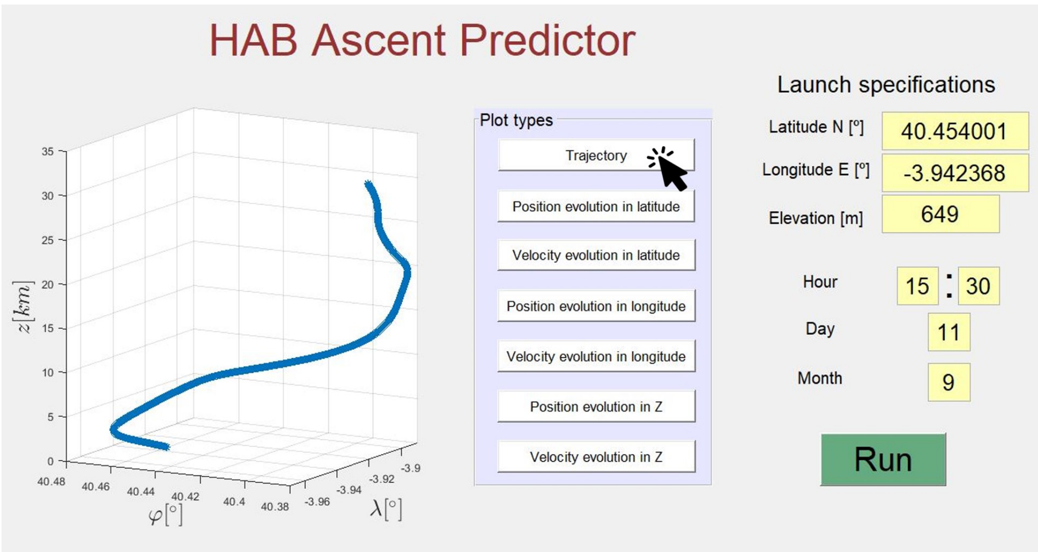

Figure 35: Trajectory

4.2.1 Trajectory analysis

As previously stated in methodology section, since there is no vertical velocity, the contribution of the wind corresponds to the ones in longitude and latitude directions. The balloon will ascent due to Archimedes' principle and will be moved by the gust of winds.

This can be appreciated in figures 36 and 37. In latitude and longitude directions, the positions has been calculated by integration, so from average results ending with a smooth balloon trajectory.

Meanwhile, the velocity undergoes several changes because it is really influenced by winds, which have been interpolated from NOAA database. It can be observed that some wind gusts appears during the ascent trajectory.

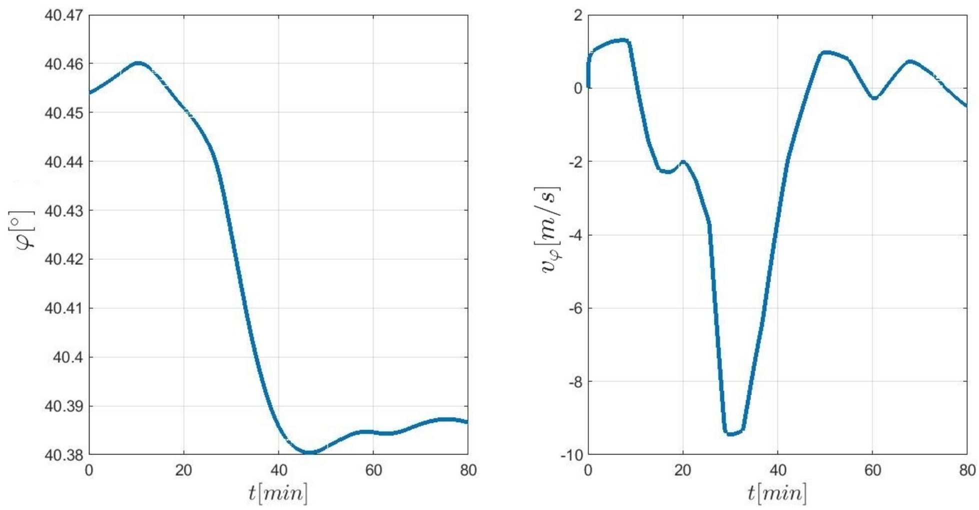

Figure 36: Position and velocity evolution in latitude direction

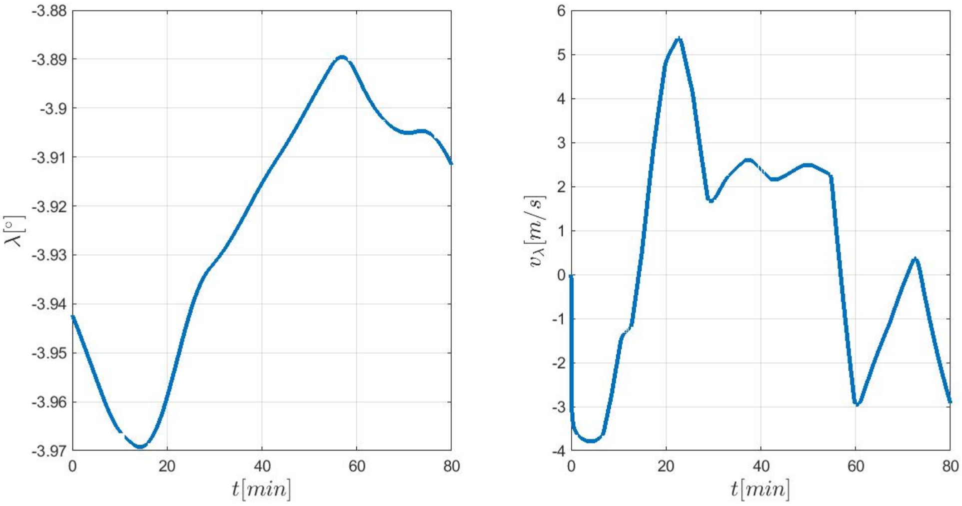

Figure 37: Position and velocity evolution in longitude direction

On the other hand, the position in z direction follows a smooth line that increases until it reaches 30 km, where the balloon bursts.
At the beginning of the ascent, the velocity undergoes a drastic increase to the quasi-steady value (almost 5m/s). This fact means that the balloon is nearly in equilibrium at all times. The velocity is continuously increasing is due to the fact that the air density, and therefore drag, decreases with altitude more rapidly than lift does, hence, the velocity increases.

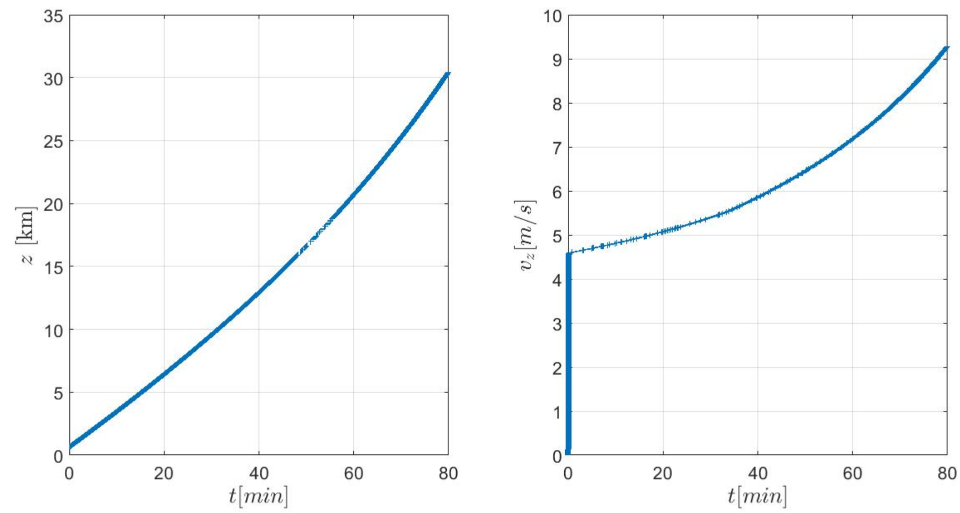

Figure 38: Position and velocity evolution in z direction

4.2.2 Comparison

In figure 39 and 40 are plotted the trajectories that the balloon would follow if it were launched at the same location but in different dates (each of the wind data was collected at 21:30). It can be observed that winds behave really differently depending on the date, so they change completely the trajectory of the balloon, although they only differ one day one from the other.

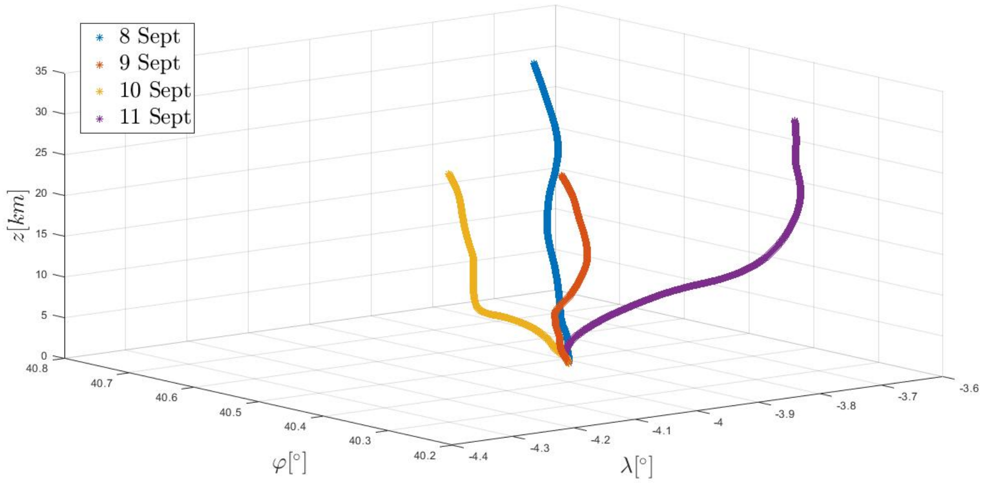

Figure 39: Date comparison - MATLAB

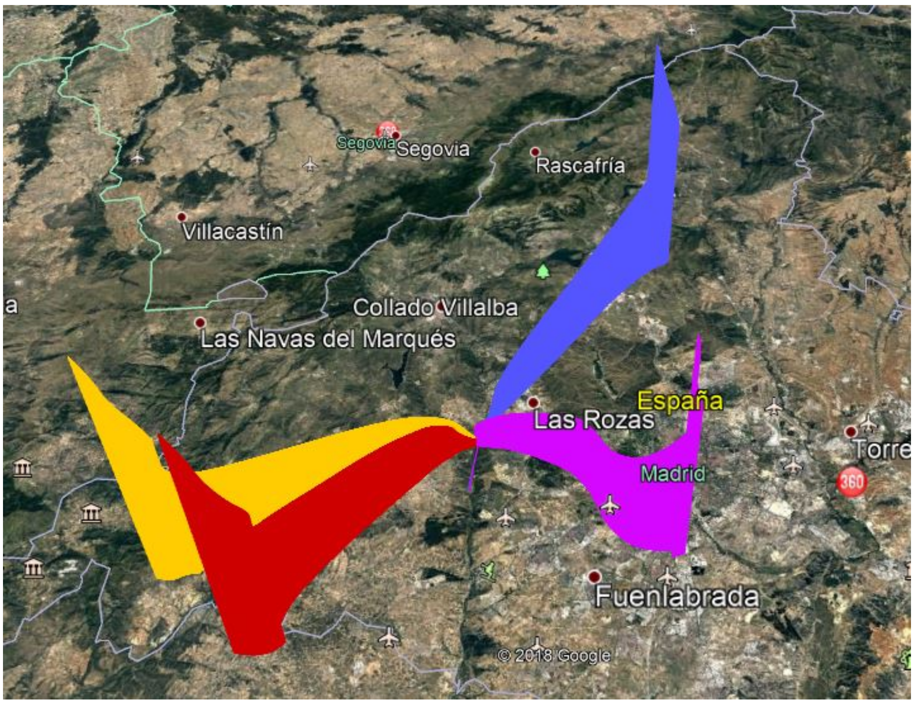

Figure 40: Date comparison - Google Earth

5 Project management

A previously stated, the whole experiment is organized in different areas and each of them has its own responsibilities to meet the final goal, that is the balloon launch. The electronic group is in charge of developing a GPS able to track the balloon coordinates during the whole flight. Meanwhile, the ascent is developed by aerodynamic equations and to show the trajectory of balloon for determining the proper launch site. For its part, a parachute has to be designed for a suitable descent and a security study is developed by the safety group.

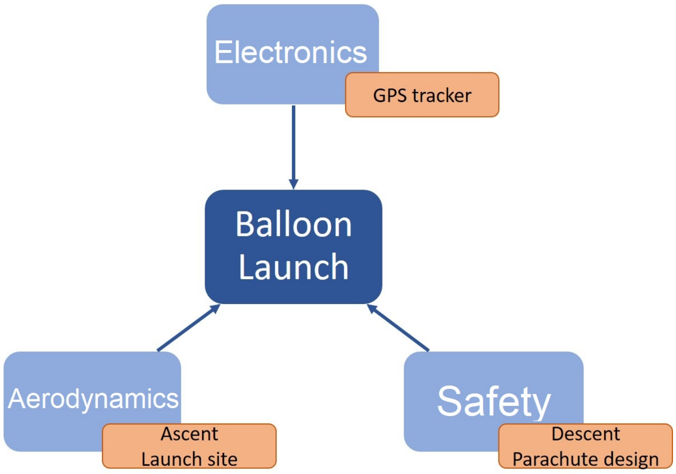

Figure 41: Project organization

5.1 Project planning

Technical concerns are extremely important, but the planning of the project must be accurately performed for a successful development. Engineering projects commonly follows this system workflow, that was used for managing this project. Note that this planning is focused on this present project, which is inside the aerodynamic group.

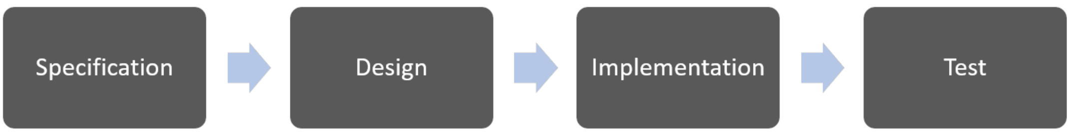

Figure 42: Systems engineering workflow

First of all, the specifications were defined and designated to each of the groups involved. This includes regular meetings for exchanging information yielding to specific requirements that the system have to fulfill. For example, the electronic group established that the payload is around 1 kg and the aerodynamic group has to find a balloon able to withstand at least this load.

After that, the project proceeds to the design part, where the whole system is designed according to previous requirements. The balloon selection and the obtaining of the hydrogen amount belongs to this phase.

Next step consists of implementing theoretical knowledge into a real solution. The implementation, in aerodynamic terms, have involved solving the equations of motion and performing an application to the user.

Last but not least, the testing phase shows if the results are correct, which tends to be the most critical part. For this particular project the test can be divided into two ones: lab test and flight test. Lab testing is performed via computer analysis of the trajectory results by comparing them with other predictors. On the other hand, flight test will consist of comparing the results with actual balloon launching, either launching a balloon by the group or comparing data from previous experiments.

This workflow has been followed during a whole year and the planning is shown in next figure.

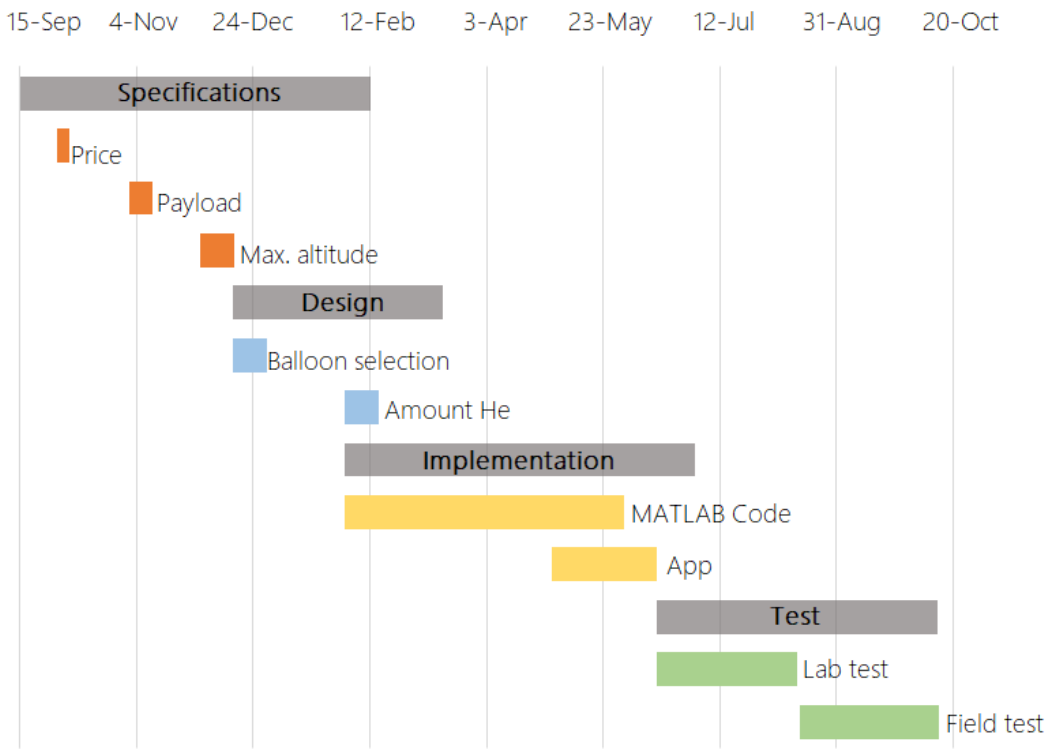

Figure 43: Gantt chart planning

5.2 Socioeconomic framework

It has been ahead in the current framework section (2.1), the feasibility of the project regarding technology and material. In this section, it will be analyzed in more detail the social and economical environment in which this technology is involved.

High altitude balloons are immerse in a growing framework. New applications are appearing covering different areas, from research to more innovative projects. This fact produces an increase of the capabilities of this type of balloons. Some of them are itemized below: [28]

- **Station-keeping**: the ability to place the balloon in a predetermined location instead of moving by winds.
- **Point-to-point flight**: definition of balloons trajectories that do not depend on atmospheric conditions.
- **Routine-long duration flight**: week and months flights.
- **Onboard personnel**: possibility to fly over the Stratosphere ascending with the help of a balloon. This innovative idea will be further explained in more detail in Section 7-TFG Emprende.
- **Advanced balloon manufacturing**: manufacturing techniques and artificial intelligence has promoted the improvement of the manufacturing processes that by now are costly and limited.

These capabilities will stir up the aerospace sector creating new employments and projects that may sound improvable so far, but as it will be explained in Section 7-TFG Emprende, these ideas are closer than the world thinks.

5.3 Project budget

It is of paramount important that a budget of the project is established to study its feasibility in accordance with the current regulation, situation and framework. The project budget is a financial disposal limits that are required for its development and implementation. It contains the maximum capital, work costs and the resources needed. [29]

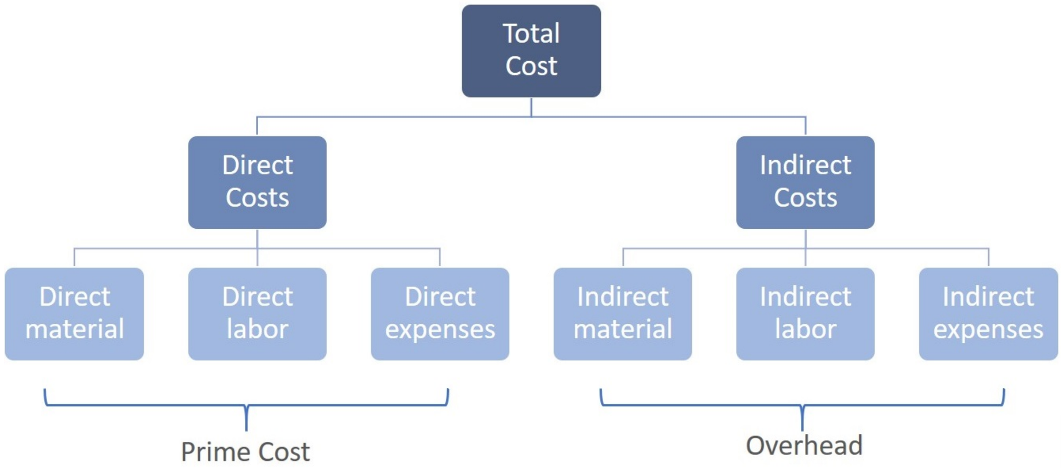

Figure 44: Cost classification

5.3.1 Direct costs

Direct labor

The labor cost refers to the workers who are contributing directly on the project. [30] The bachelor thesis is equal to 12 university credits, which is 360 h of student work. But this project has been around 550 h of work, taking as a reference the average salary of an engineering internship (6€/h). Moreover, assuming that the professor has dedicated 100 h to the project, regarding the average cost of a doctor to the university (See Appendix D).

Worker	Price [€/h]	Time [h]	Total price [€]
Student	6	550	3300
Supervisor (doctor)	27.2	100	2720

Table 5: Direct labor

Direct expenses

Direct expenses include the expenses that are charged for a process or service given. [30] For this project a notification is required for launching the balloon.

Item	Type	Price [€]
MATLAB License	Student R2018b, All toolboxes	412
Windows License	Windows 10 Home	145

Table 6: Direct expenses

5.3.2 Indirect costs

Indirect material

Indirect materials are those that are used during the whole process but they are not included in the final system. [30] In this section the laptop amortization is included as indirect cost.

Assuming a purchasing price of 500 €, then:

$$Depreciation_{annual} = \frac{Price_{purchase}}{lifetime} = \frac{500}{7} = 71.43\frac{€}{year} \quad (58)$$

Taking that the average use of the computer is 5h/day and that the computer has been used for project purposes during 450h:

$$Cost_{actual} = \frac{Depreciation}{year}time = \frac{71.43€}{1year * 365\frac{day}{year} * 5\frac{h}{day}}450h = 17.61€ \quad (59)$$

Item	Price [€]
Laptop	17.61
University material	60

Table 7: Indirect material

University material includes the student material (books, USB, pens, calculator, etc)

Indirect expenses
Indirect expenses are those which are incurred by the university in carrying out their total activities and cannot be conveniently allocated to the project. [30] This section includes lighting expenses.

For the case of the computer consumption, according to the specifications of the computer, the CPU, when it is on, consumes 50.56W and the screen 18.84W. Moreover, 3 bulbs are required while working, with a consumption of 60W each one. Knowing that the average light price in Spain is 0.13754 €/kWh, the total lighting price can be computed:

$$Price_{light} = \frac{550h \cdot (50.56 + 18.84 + 3 \cdot 60)\cancel{W}}{10^3\cancel{W}}kW \cdot 0.13754\frac{€}{kWh} = 18.87€ \quad (60)$$

Since Spain levies the lighting to 21%, the lighting cost becomes 22.83 €.

Item	Price [€]
Lighting	22.83

Table 8: Indirect expenses

5.3.3 Total cost

Cost type	**Price [€]**
Direct material	-
Direct labor	6020
Direct expenses	512
Indirect material	77.61
Indirect labor	-
Indirect expenses	22.83
Total cost	6632.44

Table 9: Total costs

6 Conclusions and further considerations

The main objective of this project has been the developing of a HAB trajectory predictor that is able to compute ascent paths with a better accuracy than current ones, considering a variable ascent velocity.

Firstly, an elastic study has been performed to analyze if the elastic terms have to be taken into account. It has been observed that elastic effects appear at really high altitudes, out of the range of this balloon. Therefore, no elasticity is considered when implementing the equations of motion.

Then, the flight dynamics during the ascent has been evaluated. Position and velocity evolution are displayed in latitude, longitude and z directions, being the first two ones highly dependent on the date of launch. Meanwhile, in z-direction an increase in velocity (from 5 to 9 m/s) has been appreciated.

The software has been implemented in an interactive way. The " HAB Ascent Predictor" app allows the user to introduce the date and site of launch resulting on a trajectory prediction and being able to plot position and velocity evolution along time.

It is of paramount importance to state that this prediction can be also extrapolated to other types of balloons, like the open ones taking into consideration the loss of gas.

Finally, it must be stated that for a complete and reliable prediction, the balloon will be launched in a near future and then, the theoretic results can be compared with the experimental ones, being possible to improve the designed solution. Moreover, the possibility to introduce balloon parameters in the " HAB Ascent Predictor" is left as a further development.

7 TFG Emprende

The " TFG Emprende" is an instrument to promote students to get involved into undertaking culture and innovation. The main objective is to enable students to create a commercial project as a result of their bachelor's thesis based on innovation and new technologies.

Different on-site workshops were given by professionals of the area, allowing the students to learn several concepts of the sector and how to apply them to real situations, companies and to the innovative project itself.

" TFG Emprende" is divided into two blocks:

1. **Innovation and competitive advantage**

   The objective of this first block is to understand the concept of innovation and apply innovative ideas to the bachelor's thesis. An innovation Canvas model has to be developed according to the following figure, that is called Innovation Pivot Framework. [31]

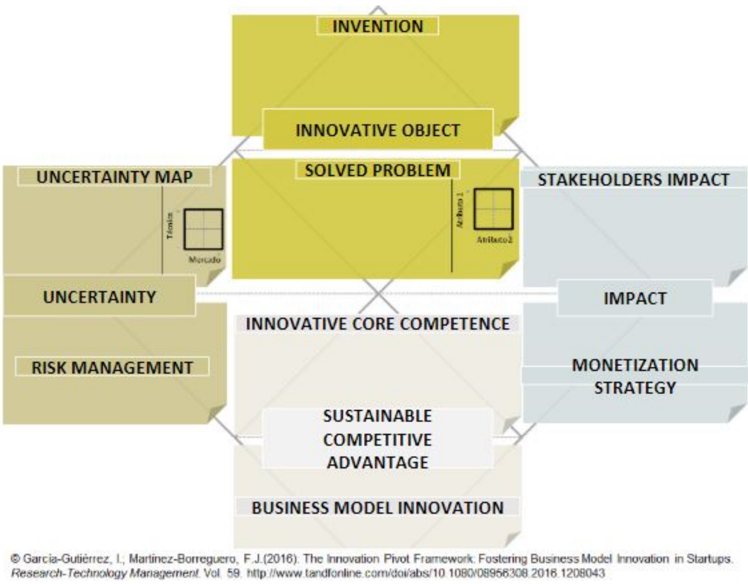

Figure 45: IPF [31]

The model is dived into different areas:

- **Innovation**: in which invention is the project based on. Identification of the problem.
- **Impact**: maximum scope of the project. Stakeholders identification.
- **Sustainable competitive advantage**: identification of the key factor of the project.

- **Uncertainty**: PESTEL analysis that provides the level of uncertainty of the project.

Figure 46: PESTEL analysis [31]

2. **Business Canvas model**

This block consists of understanding the difference between business plan and business model; between startup and company. Moreover different types of business models are explained and the students have to create a business Canvas model applied to their projects. This model is the previous step to the business plan. It is a dynamic model that changes over time while the initial hypothesis are validated. This model is used to clearly define the offer that this project provides, the channels that are going to use to sell the product, the key partners involved, the strategy to follow and the revenue streams. [32]

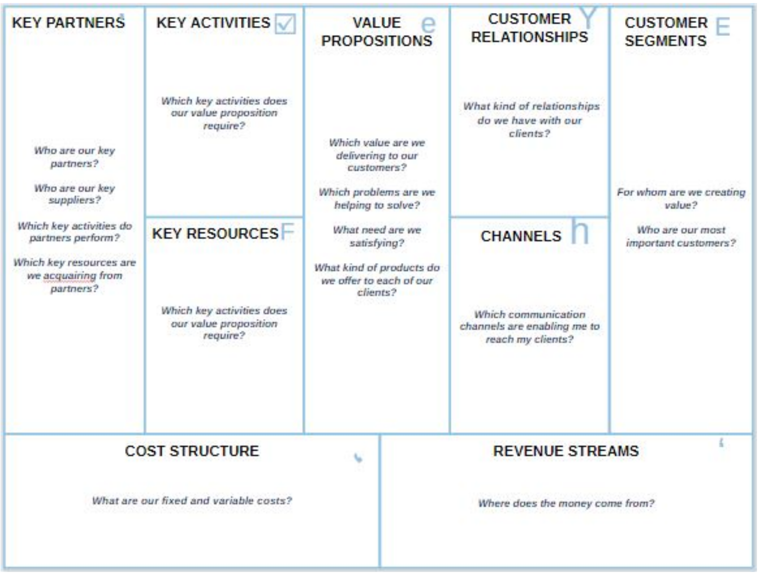

Figure 47: Business Canvas model [32]

Once the model is performed, it has to be iterated along time. Also, it is important to create a minimum value product (MVP) and analyze it in the target market.

7.1 Project proposal

As previously mentioned, high-altitude balloons can be used for meteorological purposes due to the large altitude that they can reach. Moreover, some entrepreneurs have enlarge the application of these balloons. For example, "Zero 2 Infinity" company provides access to space by means of stratospheric balloons. You can put your satellite with one of these balloons. Bloon is one of its more ambitious proposal that consists of sending people to the Stratosphere in a capsule elevated by a high resistant balloon. [33]

Figure 48: Bloon project - Zero 2 Infinity [33]

Another innovative example with balloons is the case of Loon, the Google's project that would provide internet connectivity around the world with a balloon network. [34]

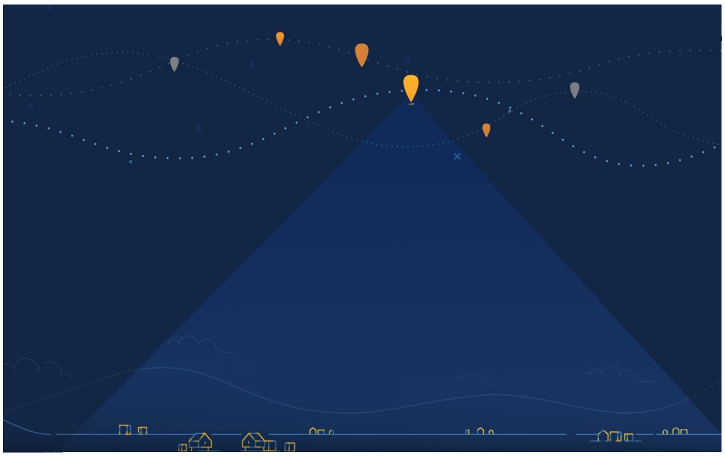

Figure 49: Loon project - Google [34]

Based on this last idea, the proposed project is to provide coverage to hospitals in developing countries. This project could increase the management and organization of hospitals and could accelerate communications of patients database information. The clients of this product would be NGOs that contribute to the improvement of health service and want to enhance their communications.

This is the minimum viable product that can be extrapolated to the private internet connection and to other countries. However, the first approach of this project is for social purposes.

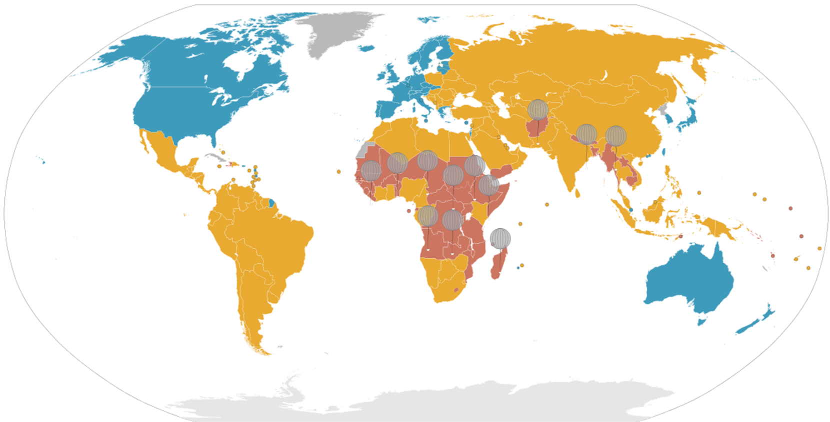

Figure 50: Project proposal

Innovation, development, investigation, proactivity, new technologies and social improvement. This project combines and commits to each of them. Don't you think that it be worth trying?

"I can't change the direction of the wind,
but I can adjust my sails to always reach my destination"

Jimmy Dean

References

[1] Enrique Barbero Pozuelo. *Historia de la tecnología aeroespacial: Lighter than air.* (Visited on 06/10/2018).

[2] The Editors of Encyclopaedia Britannica. “Archimede’s principle”. In: (June 1998). URL: https://www.britannica.com/science/Archimedes-principle (visited on 06/11/2018).

[3] Pierre Bauduin. “Francesco Lana de Terzi (1631-1687)”. In: (May 2012). URL: http://weebau.com/history/lanadeterzi.htm (visited on 06/13/2018).

[4] The Editors of Royal Society of Chemistry. URL: http://www.rsc.org/periodic-table/element/1/hydrogen (visited on 08/18/2018).

[5] *The Hindenburg Disaster.* URL: https://www.airships.net/hindenburg/disaster/ (visited on 09/01/2018).

[6] Javier Gacría Heras. *History of Air Transport slides.* (Visited on 08/10/2018).

[7] Tom Harris. “How Hot Air Balloons Work”. In: (Feb. 2001). URL: https://science.howstuffworks.com/transport/flight/modern/hot-air-balloon.htm (visited on 07/15/2018).

[8] EOS Project Science Office. “Alfred Wegener(1880-1930)”. In: (Feb. 2001). URL: https://earthobservatory.nasa.gov/Features/Wegener/wegener_3.php (visited on 09/01/2018).

[9] The Editors of High Altitude Science. “Intro to Weather Balloons”. In: (-). URL: https://www.highaltitudescience.com/pages/intro-to-weather-balloons (visited on 07/16/2018).

[10] NASA’s Balloon Program Office. “Scientific Balloons”. In: (-). URL: https://sites.wff.nasa.gov/code820/faq.html#anchor14 (visited on 07/16/2018).

[11] NASA’s Balloon Program Office. “Scientific Balloons: How big is big?” In: (-). URL: https://sites.wff.nasa.gov/code820/outreach_big.html.

[12] “Super-Pressure balloons”. In: (-). URL: http://hibiscus.projet.latmos.ipsl.fr/projet/HIBISCUS/en/many/spb.html.

[13] Javier Lloret. *Introduction to Air Navigation, Chapter 7. Airspcae Management.* v. 2. Jan. 2016. (Visited on 06/20/2018).

[14] *ICAO Annex 2, Rules of the Air.* Tenth edition. July 2005, pp. 1–3, 1–5. (Visited on 06/20/2018).

[15] *Insignia - Enaire.* URL: https://ais.enaire.es/insignia/navegador/.

[16] KS FG. “ORISON Feasibility Report: Regulations in Spain”. In: (Sept. 2017). (Visited on 04/01/2018).

[17] *Commission Implementing Regulation(EU) N. 923/2012, Appendix 2.* Oct. 2012, (visited on 06/22/2018).

[18] *FCC Electronic Code of Federal Regulations*. URL: https://www.ecfr.gov/cgi-bin/text-idx?rgn=div8&node=47:2.0.1.1.2.8.27.12 (visited on 08/05/2018).

[19] *Hab hub predictor*. URL: http://predict.habhub.org/.

[20] *ASTRA flight planner*. URL: http://astra-planner.soton.ac.uk/.

[21] *PAWAN balloons*. URL: http://www.pawanexport.com/Sounding-Balloons.shtml.

[22] Javier Hilario Montes. *Notes Aircraft Design - Chapter 1: Generalities and operating environments*. (Visited on 07/10/2018).

[23] Landon M. Kanner. "Inflation of strain-stiffening rubber-like thin spherical shells". In: (), pp. 1–5. URL: https://earthobservatory.nasa.gov/Features/Wegener/wegener_3.php (visited on 09/01/2018).

[24] Manuel García Villalba. *Introduction to Mechanics of Flight*. v. 3.03. June 2015, pp. 46–50. (Visited on 06/10/2018).

[25] *NOAA: About Our Agency*. URL: https://www.noaa.gov/about-our-agency.

[26] NCEP Internet Services Team. *GFS documentation*. URL: http://nomads.ncep.noaa.gov/txt_descriptions/GFS_doc.shtml.

[27] Donna Roberts. *Prisms*. URL: https://mathbitsnotebook.com/Geometry/3DShapes/3DPrisms.html (visited on 08/10/2018).

[28] Alan Stern. "A 21st century renaissance in high altitude ballooning". In: (2016). URL: https://spacenews.com/a-21st-century-renaissance-in-high-altitude-ballooning/.

[29] "Project budget: The financial framework of a project". In: (-). URL: https://www.inloox.com/project-management-glossary/project-budget/.

[30] Aisha P. "Classification of Costs: 5 Types — Accounting". In: (-). URL: http://www.accountingnotes.net/cost-accounting/cost-classification/classification-of-costs-5-types-accounting/10178.

[31] Vicerrectorado de Investigación y Transferencia. *TFG Emprende: Bloque de innovación*. (Visited on 03/10/2018).

[32] Vicerrectorado de Investigación y Transferencia. *Modelo Business Canvas*. (Visited on 05/10/2018).

[33] *Bloon: the day trip of a lifetime*. URL: http://www.zero2infinity.space/bloon.

[34] *Loon: connect people everywhere*. URL: https://loon.co/.

Annex A: Acronyms

Acronym	Definition
AD	After Death
ASTRA	Atmospheric Science Through Robotic Aircraft
BC	Before Christ
CUSF	Cambridge University Spaceflight
EASA	European Aviation Safety Agency
GFS	Global Forecast System
GPS	Global Positioning System
HAB	High-Altitude Balloon
IPF	Innovation Pivot Framework
MVP	Minimum Value Product
NDB	Non-Directional Beacon
NGO	Non-Governmental Organization
NOAA	National Oceanic Atmospheric Administration
NOMADS	NOAA Operational Model Archive and Distribution System
NOTAM	NOtice To AirMen
PESTEL	Political Economic Social Technological Environmental Legal
SFC	Superficie (Surface)
SSR	Secondary Surveillance Radar

Table 10: Acronyms

Annex B: Pawan 1600 Specifications

PAWAN
433/2 Pune Nasik Road,
Kasarwadi, Nasik Phata,
Pune - 411034, India
T + 91-20-27125019
F + 91-20-27125622
info@pawanexport.com
www.pawanexport.com

PAWAN

Meteorological Balloons
Meteorological Instruments
Meteorological Consumables

Technical Specification for 1600gm Meteorological Balloon

SPECIFICATION	CPR-1600
Weight, gm	1600
Payload, gm	1100
Recommend Free lift, gm	1310
Nozzle lift, gm	2310
Gross lift, gm	3910
Diameter at release, m	1.94
Rate of ascent, m/min	325
Diameter at burst, cm	950
Bursting altitude, km	34
Neck diameter, cm	8.5
Neck length	20-22
Colour	Uncolored/White

Figure 51: Pawan 1600 specifications [21]

Annex C: MATLAB code

The MATLAB code used for this project has been uploaded to the following Dropbox folder:

https://www.dropbox.com/home/High-altitude%20Trajectory%20Predictor

Equations_of_motion is the main file that has to be running to plot the trajectory, position and velocity of a balloon in an specific site and date of launch. Note that the wind data have to be introduced into the $nco2$ variable as: $nco2 = ncgeodataset('./Folder/gfs.xxxx.pgrb2.0p25.fxxx')$.

Also, the HAB Predictor app has been uploaded as: *HAB_Ascent_Predictor.m*

Annex D: Recruitment labor table

COSTE MENSUAL DE CONTRATACIÓN LABORAL*, SEGÚN TABLAS PARA 2016

	Bachiller / FP2		Titulado Medio		Titulado Superior				Titulado Doctor			
					MÍNIMO		MÁXIMO		MÍNIMO		MÁXIMO	
JORNADA	Salario bruto	Coste proyecto	Salario bruto	Coste proyecto	Salario bruto	Coste proyecto	Salario bruto	Coste proyecto	Salario bruto	Coste proyecto	Salario bruto	Coste proyecto
17,5H	910,00	1236,24	1056,35	1435,06	738,67	1003,49	1265,46	1719,13	861,12	1169,84	1593,04	2164,16
22,5H	1170,00	1589,45	1358,17	1845,08	949,72	1290,20	1627,02	2210,32	1107,16	1504,09	2048,20	2782,49
27,5H	1430,00	1942,67	1659,98	2255,09	1160,77	1576,91	1988,58	2701,50	1353,20	1838,33	2503,35	3400,82
32,5H	1689,99	2295,87	1961,80	2665,11	1371,82	1863,63	2350,14	3192,68	1599,23	2172,57	2958,51	4019,16
Completa (37,5H)	1949,99	2649,08	2263,61	3075,13	1582,87	2150,34	2711,70	3683,86	1845,27	2506,81	3413,67	4637,49
	Coste hora=	20,18	Coste hora=	23,43	Coste hora=	16,38	Coste hora=	28,07	Coste hora=	19,10	Coste hora=	35,33

* ***Técnicos de apoyo a la investigación y personal investigador.*** *Para contratos predoctorales consultar los costes al Servicio de Investigación*

***SALARIO ANUAL para cada jornada* = Salario Bruto x 12**

***COSTE PROYECTO anual* = Coste proyecto x 12**

Base máx cotización SS 2016: 3.642,00 €

Figure 52: Recruitment labor - UC3M